

Toward an Understanding of Global Change  
Initial Priorities for U.S. Contributions to the  
International Geosphere-Biosphere Program

, National Research Council, Washington, DC

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# Toward an Understanding of Global Change

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Geosphere-Biosphere Program*



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# **Toward an Understanding of Global Change**

## ***Initial Priorities for U.S. Contributions to the International Geosphere-Biosphere Program***

Committee on Global Change  
(U.S. National Committee for the IGBP)  
*of the*  
Commission on Life Sciences  
Commission on Physical Sciences,  
Mathematics, and Resources  
Office of International Affairs  
Commission on Behavioral and  
Social Sciences and Education  
National Research Council

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NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the panel responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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## Preface

Throughout its life on this earth, our human species has faced a varied and ever-changing environment. We humans have enjoyed great success. We have learned how to survive, and indeed how to prosper, in winter's cold and summer's heat, and in environments as diverse as Amazonian jungles, Saharan deserts, and arctic steppes. We have not only adapted to the world as we found it; we have turned forests into fields, bent rivers to water deserts, and wrested fuels and goods from the earth itself.

Our success has not been achieved without cost. In exploiting the earth's riches for our ends, we are necessarily changing our planet in myriad ways. Sophisticated observers on Mars would note not only our cities, our highways, and the Great Wall of China, but also the disappearance of tropical forests, rapid changes in the composition and radiative characteristics of our atmosphere, and the dramatic annihilation of our protective ozone layer over the Antarctic. They might speculate that further changes could eventually affect the planet's ability to sustain life. They might further suppose that a species clever enough to produce such changes would be astute enough to worry about them. Fortunately, they would be right.

Concern about the long-term changes humanity is inducing in its planetary environment has indeed been mounting for some decades in the scientific community, and for some years in the broader communities of the general public. Fortunately again, this concern about

human-caused change has built upon a long-growing scientific preoccupation with natural change in the earth. Scientists have learned that the earth's history has been characterized by ceaseless change, that most of mankind's history has been lived in a wintry glacial age, and that our vaunted civilization has flowered in a single brief interglacial summer. But while we have learned much about what has happened, we still understand discouragingly little about why it happened.

We have, however, learned that we have no hope of understanding the changes of the past, and still less of predicting the changes of the future, by looking piecemeal at one or another aspect of this complicated planet. If we are concerned with the decades and centuries ahead, we cannot ignore the linkages that have shaped the planet's past and present. The atmosphere has been largely manufactured by life; the ocean's currents have been driven by the atmosphere, and the ocean's living things have been nourished by airborne dust and riverine sediments; and, throughout the ages, climate and life have been inescapably intertwined. We must dare to seek an understanding of the earth as a single system of which we ourselves are an increasingly important part.

This challenge motivated groups of scientists in the early years of this decade to advance the venturesome proposal that science attempt fully integrated studies of the long-term future and continued habitability of the globe. These proposals led to searching studies of the goals and requirements for research and observational efforts in earth system science to study the problems of global change. Encouragingly, it was concluded that advances in our capabilities to observe the earth, notably from the vantage point of space, and in our ability to deal with massive and diverse data, made such a quest feasible. Thus, advances in both understanding and capabilities led to proposals for the development of an International Geosphere-Biosphere Program (IGBP) to focus the efforts of the world's scientists on the problem of global change.

The objective of the IGBP is to develop the scientific understanding needed to anticipate future changes in the earth system. Such predictive information provides the foundation for decision makers to develop policies that respond to global change. Thus, in addition to the immense scientific challenge, the scientific community will face the equally difficult challenge of effectively communicating the results of the IGBP to those responsible for formulating policies.

Turning such broad goals into concrete projects and plans is

no easy task. It demands that scientists shed their long-embedded traditions of narrow disciplinary study, and summon the courage to attack together problems that are both exceedingly difficult and surpassingly urgent. Within the United States, many elements of a broad research program in the earth sciences are already being developed within the federal agencies. These federal efforts will provide the indispensable foundation for U.S. contributions to the worldwide study of global change problems. In parallel, plans for the IGBP are being elaborated by a Special Committee of the International Council of Scientific Unions. Thus organized programs on the problems of global change are currently in their preparatory phases, in which scientific goals are being sharpened, potential projects explored, and resource requirements identified. The task of the Committee on Global Change is to serve as a channel for information, advice, and guidance among the U.S. scientific community, the federal agencies, and the international planning mechanisms in the development and implementation of these studies of global change.

The purpose of this report is to identify early U.S. contributions to the internationally defined IGBP during this preparatory phase of its planning. The initiatives proposed were based upon a review by our committee of the current state of knowledge of the earth system as seen from several discipline-oriented perspectives. These reviews were organized by various members of the committee with the involvement of numerous experts from the scientific community. For example, small workshops were held on biological systems and dynamics in terrestrial and marine systems, and on biogeochemical dynamics. A number of experts were also consulted to provide comments on background documents prepared by committee members on the climate and hydrologic system and on the human dimension of global change. These efforts culminated in the background papers included in Part II of this report.

These background papers provided the basis for a week-long study by the committee, together with invited experts from academia and government, held in March 1988 at Oracle, Arizona. The committee sought to identify a small number of scientific questions that demanded to be addressed by the U.S. scientific community now, in the preparatory phase of the IGBP, and regardless of the program's ultimate design. Thus the committee emphasized questions that were fundamental to the understanding of long-term changes in the earth system, and issues that—because they cut across conventional disciplinary perspectives—were not being adequately addressed in

ongoing programs. Part I of this report presents the results of that analysis. As the international and national programs evolve, the ongoing dialogue within the scientific community on the questions that need to be addressed will continue. Thus the committee expects to supplement these recommendations regarding early initiatives in the program with more complete studies, reviews, and scientific plans.

Throughout the preparation of this report, an enormous number of people aided the committee. We are greatly indebted to the scientists listed in connection with the individual background papers, who gave so freely of their time to participate in workshops and in the drafting and review of manuscripts. We also thank the many colleagues who reviewed early versions of the report.

A number of representatives of the federal agencies participating in the Committee on Earth Sciences of the Federal Coordinating Council on Science, Engineering, and Technology have worked exceptionally closely with our committee, and have greatly enriched our deliberations. Within the National Research Council, our committee has operated under the supervision, and with the steadfast support, of an ad hoc coordinating committee consisting of the chairmen of the Commissions on Physical Sciences, Mathematics, and Resources; Life Sciences; and Behavioral and Social Sciences and Education; and the foreign secretary. With the aid of these groups, we believe that we have forged a new and uniquely productive form of interaction and partnership among many federal agencies with diverse missions and many scientific disciplines with diverse concerns and constituencies.

Finally, we are most appreciative of the support of the committee's staff at the National Research Council: John Perry, Ruth DeFries, Doris Bouadjemi, and Cristina Rosenberg.

Harold A. Mooney, Chairman  
Committee on Global Change

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## Summary of Recommendations

Human activities are currently leading to changes in the global environment at virtually unprecedented rates, with potentially severe consequences for our future welfare. Increases in carbon dioxide and other greenhouse gases, concerns for climate change, the appearance of the antarctic ozone hole and worldwide depletion of the ozone shield, tropical deforestation, and a host of other changes in our environment have captured the attention of scientists, the public, and policymakers. *The problem of global environmental change is crucial and urgent.*

For scientists, understanding the changes now in progress—both natural and anthropogenic—and predicting their future course are unprecedented challenges. New capabilities for observing the earth and new understanding of natural processes have led to a new conception of the earth as an integrated whole and to the development of evolving, extremely broad research programs on global change. Such programs must draw upon the capabilities of scientists in many disciplines and many nations and must build upon the foundation provided by many ongoing national and international programs.

In the United States, the program on global change includes the study of biogeochemical dynamics, ecological systems and dynamics, climatic and hydrologic systems, human interactions, earth system history, solid-earth processes, and solar influences. The fundamental

paradigm is that the prediction and ultimate management of environmental problems inescapably require development of a new earth system science aimed to improve understanding of the earth as an integrated whole.

In the international scientific community, the International Council of Scientific Unions has organized the International Geosphere-Biosphere Program (IGBP) to address the problems of global change. The objective of the IGBP is

to describe and understand the interactive physical, chemical, and biological processes that regulate the total earth system, the unique environment that it provides for life, the changes that are occurring in this system, and the manner in which they are influenced by human activities.

The IGBP is currently in its preparatory phase, during which the program's goals and research components are slowly evolving and coming into focus.

In this report, a limited number of high-priority research initiatives are recommended for early implementation as part of the U.S. contribution to the preparatory phase of the IGBP. The recommendations are based on the committee's analysis of the most critical gaps, not being addressed by existing programs, in the scientific knowledge needed to understand the changes that are occurring in the earth system on time scales of decades to centuries. These initiatives will build upon the capabilities of the U.S. program in global change.

With this framework in mind, the committee recommends the following:

1. *Research initiatives:* The committee recommends that the early U.S. contributions to the IGBP should focus on the following five research initiatives that address key relationships in the earth system:

- *Water-energy-vegetation interactions* to develop global models of the response of terrestrial ecosystems to changes in climate, land and water use, and related factors, and to determine the reciprocal effect of such changes in terrestrial ecosystems on the climate system on regional and global scales. This research initiative requires an integrated approach of observations, experiments, and model development.

- *Fluxes of materials between terrestrial ecosystems and the atmosphere and ocean* to (1) improve understanding of ecosystem

processes most important for determining fluxes of radiatively active gases between the land and atmosphere, in order to predict how changes in climate and land use alter gas emissions, and (2) improve understanding of the effects of land use changes on nutrient transfer to river, estuarine, and ocean systems, especially to understand consequent feedbacks to climate through, for example, long-term changes in ocean productivity.

- *Biogeochemical dynamics of ocean interactions with climate* in order to predict effects of climate change on ocean biogeochemical cycles and the interactions of such cycles with climate via release and absorption of radiatively active gases. The ocean's capacity to sequester or release such gases—for example, carbon dioxide or organic sulfur species—is directly and indirectly influenced by climate.

- *Earth system history and modeling* to document changes in atmospheric composition, climate, and human activities to improve and validate models of global change. A focus on periods of rapid rates of change will provide insights into those changes that can be expected to occur with rates predicted for the future.

- *Human interactions with global change* to analyze changes in human land use, energy use, and industrial processes that drive changes in the earth system. Documentation of changes in such human activities over the last several hundred years and construction of future scenarios of human activities that contribute to global change will be part of the effort.

Steering groups of experts should be formed to develop detailed research plans for each of the five initiatives proposed above, with the committee assuring coordination and integration.

2. *Supporting research:* The U.S. component of the IGBP should serve to strengthen, coordinate, and enhance support for ongoing supportive activities in the earth sciences such as the World Climate Research Program, the Global Tropospheric Chemistry Program, the Joint Global Oceanic Flux Study, and related discipline-oriented research.

3. *Long-term measurements:* In order to document global change and provide a basis for the IGBP research program as a whole, a long-term commitment from all relevant agencies for sustained long-term measurements of key variables is required. An important element is an integrated Earth Observing System program to coordinate space-based observations.

4. *Data and information systems:* All components of the IGBP,

both U.S. and international, will require effective data and information systems, capable of making available to research investigators contemporary space- and ground-based data from observations and experiments as well as historical data sets. Establishing and maintaining an effective system for the diverse types of data that will be generated by the IGBP require an innovative, flexible, and carefully conceived approach. A Global Information System Test should be implemented to test the end-to-end performance of the information system.

5. *International Geosphere-Biosphere Research and Training Centers:* A limited number of International Geosphere-Biosphere Research and Training Centers should be established around the world as major foci for international cooperation in research and training for the study of global change. The centers would serve as appropriate to provide bases for large-scale manipulative experiments, to establish links with other international and national research and observational networks, and to serve as central repositories for observational and experimental results.

6. *Interagency coordination:* Interagency coordination between the relevant U.S. agencies for implementation of the U.S. component of the IGBP is essential to the effective management of the complex program. Existing mechanisms for such coordination under the Federal Coordinating Council for Science, Engineering, and Technology (FCCSET) Committee on Earth Sciences should continue to be strengthened, and the adequacy of this mechanism to the task at hand should be periodically reviewed.

7. *Coordination of international activities:* Innovative mechanisms should be developed for coordination of related activities of international, intergovernmental and nongovernmental organizations, and many national groups of all kinds, with the IGBP. The International Council of Scientific Unions should urgently address the international institutional arrangements for the IGBP.

## Introduction

Rapidly evolving changes in the global environment have captured the attention of scientists, policymakers, and citizens around the world: the increase of atmospheric greenhouse gases such as carbon dioxide, methane, and the chlorofluorocarbons; the expected consequent changes in global climate and sea level; global depletion of stratospheric ozone and the observed "antarctic ozone hole"; widespread desertification in many parts of the developing world; massive tropical deforestation and reduction in the diversity of plant and animal species; extensive damage to mid-latitude forests; and acidification of lakes and soils in many regions. At the least, these changes have far-reaching and potentially disruptive implications for the world's natural resources. In the worst case, the changes collectively threaten the life-support system of the earth. *The problem of global environmental change is crucial and urgent.*

The scientific community is thus urgently challenged with providing to decision makers the best possible assessments of the future course of the global environment, assessments on which policies to mitigate and adapt to these changes can be based. Over the past decade, efforts to translate the agenda of environmental problems perceived by the public into a scientific agenda of clearly posed, tractable, and prioritized research problems have led to a unifying seminal insight: We cannot hope to understand fully or to predict meaningfully the course of any single long-term environmental change

without understanding the earth system as an integrated whole, the changes in the system over the earth's history, and the ways in which anthropogenic activities interact with the system.

Contemporary advances in technology, such as the ability to observe the earth from space and the rapidly accelerating capabilities for data handling, numerical modeling, and telecommunications, make such an ambitious venture possible at this time. Historically, revolutionary scientific advances follow the development of each new instrument that extends our vision of the real world. Invention of the telescope opened our understanding of the universe. The microscope led to revolutions in biology and medicine. Today, satellite-borne sensors, worldwide communications systems, and supercomputers permit us to see our planet for the first time as an integrated whole. Disciplinary advances that have led to current understanding of the components of the earth system provide a launching point from which an integrated view of the system can be processed. Thus, because of these advances in science and technology, *understanding global environmental change is not only urgent; it is now possible.*

#### U.S. PROGRAM FOR THE STUDY OF GLOBAL CHANGE

Long-term changes in the earth have been addressed in a number of national and international programs (e.g., the Global Atmospheric Research Program, its successor World Climate Research Program, and UNESCO's Man and the Biosphere Program) that provide a strong foundation for continued progress. Most recently, an extremely broad U.S. national effort in the study of global change has evolved based on the conceptual foundation of earth system science. This conceptual framework was developed in a multidisciplinary study by the Earth Systems Science Committee of the National Aeronautics and Space Administration and has been used extensively by the National Science Foundation and the National Oceanic and Atmospheric Administration in planning their research programs on global change (ESSC, 1988). The goal of earth system science is to obtain a scientific understanding of the entire earth system on a global scale by describing how its component parts and their interactions have evolved over the earth's history, how they function, and how they may be expected to continue to evolve. Because of the increasing evidence of potentially significant human influences on the earth system, the U.S. program focuses on the research necessary to

predict those changes that will occur in the next decades to centuries, both naturally and through interactions with human activities.

Currently, the U.S. program on global change centers on the study of the following seven elements identified by the Committee on Earth Sciences of the Federal Coordinating Council for Science, Engineering, and Technology (Committee on Earth Sciences, 1988):

- *Biogeochemical dynamics* to study the sources, sinks, fluxes, and interactions between mobile biogeochemical constituents within the earth system, with a particular focus on water, oxygen, carbon, nitrogen, sulfur, phosphorus, and the halogens.
- *Ecological systems and dynamics* to study the responses of ecological systems, both marine and terrestrial, to changes in global environmental conditions and the influence of biological communities on the atmospheric, climatic, and oceanic systems.
- *Climatic and hydrologic systems* to study the physical processes that govern the climate and hydrological system—comprising the atmosphere, hydrosphere (oceans, surface and ground water, and so on), cryosphere, land surface, and biosphere.
- *Human interactions* to study (1) the impact of human activities on the global environment, including releases of nutrients, toxins, chemicals, and trace gases and changes in the use and cover of the land, such as desertification, and (2) the impact of changing global conditions on human activities.
- *Earth system history* to uncover the natural record of environmental change contained in rocks, terrestrial and marine sediments, glaciers and ground ice, tree rings, geomorphic features, and other direct or proxy documentation of past environmental conditions.
- *Solid-earth processes* that affect the life-supporting characteristics of the global environment, especially those processes (e.g., volcanic eruptions) that take place at the interfaces between the earth's surface and the atmosphere, hydrosphere, cryosphere, and biosphere.
- *The solar influence*, including studies of the atmospheric response to changes in solar trends including variations in solar output and the earth's orbital elements.

#### THE INTERNATIONAL GEOSPHERE-BIOSPHERE PROGRAM

Internationally, a new interdisciplinary program in which scientists from many nations and diverse disciplines can work together



to understand the earth as an integrated whole is being planned to augment the ongoing efforts dealing with individual components of the earth system. The internationally defined objective of the *International Geosphere-Biosphere Program (IGBP)—A Study of Global Change*, launched in 1986 by the International Council of Scientific Unions (ICSU, 1986), is

to describe and understand the interactive physical, chemical, and biological processes that regulate the total earth system, the unique environment that it provides for life, the changes that are occurring in this system, and the manner in which they are influenced by human activities.

Priority in the IGBP falls on

those areas of each of the fields involved that deal with the key interactions and significant change on time scales of decades to centuries, that most affect the biosphere, that are most susceptible to human perturbation, and that most likely lead to predictive capability.

Implementation of the IGBP clearly calls for interdisciplinary, international research on an unprecedented scale. The success of the program will depend on the ability to document global change through long-term and sustained measurements of key variables in the earth system through an expanded space- and ground-based composite observing system. Modeling global change, a critical element of the program, calls for extended research by interdisciplinary teams employing advanced computational capabilities. Thus implementation of the program requires a long-term political commitment to develop the scientific basis upon which policy decisions can be made.

The operational framework for the IGBP must include investigation and understanding of phenomena of time scales both shorter and much longer than the decades to centuries scale for which predictive capability is needed. Studies under the World Climate Research Program of the response to the short-term phenomena of El Niño, for example, provide information about the modes and rates of response of the biota to changing environmental conditions. Long-term phenomena revealed in the record of the past provide essential background against which these more immediate changes can be evaluated. Similarly, although the focus of the program is on global scales, it must include those regional-scale studies that are needed both to understand the whole-earth system and to anticipate significant regional impacts of global change.

The international scientific community is currently engaged in the preparatory phase of the IGBP under the guidance of the ICSU Special Committee for the IGBP. During this period, the program's goals and research components will evolve and come into focus. Some operational elements of the IGBP have already been initiated, and others will be implemented as planning is completed and funding becomes available. The program is expected to be fully operational in 1992. The U.S. initial contributions to the IGBP, discussed in this report, together with U.S. contributions to related ongoing programs, will form part of this evolving international effort.

### OBJECTIVES AND ORGANIZATION OF THIS REPORT

This report specifically proposes a limited number of early U.S. initiatives, based on the internationally defined goals for the IGBP, that will contribute significantly both to our national interests and to the IGBP. The proposed initiatives build on the several ongoing national and international programs addressing problems of global change relevant to the IGBP, notably the projects organized under the World Climate Research Program and the U.S. National Climate Program. The proposed initiatives are designed to supplement such existing efforts, not to supplant them.

In formulating its recommendations, the committee had no intention of constraining either the IGBP or the broad U.S. program of research in the area of global change to only these specific early initiatives. These areas for initial focus are intended to provide a framework for early U.S. contributions to the IGBP rather than to include all research that will ultimately need to be carried out under the IGBP. The appropriate content and priorities of the broad U.S. effort on global change and the specific U.S. contributions to the IGBP will continue to be the subject of review and assessment by the committee.

The specific purposes of this report are as follows:

- to articulate a number of important key issues and interactions that characterize global change in the geosphere-biosphere system on time scales of decades to centuries;
- to identify the knowledge that is the most urgently needed to improve understanding of those issues and interactions; and
- to formulate initial priorities for initial U.S. contributions to the IGBP, recognizing the contributions of other ongoing and proposed programs.

Part I of the report constitutes the committee's findings, while Part II presents a group of background papers developed by working groups under the coordination of members of the committee. These papers were prepared in workshops and consultations organized by the committee, and they discuss research needs from five perspectives on the earth system: climatic and hydrologic systems, biogeochemical dynamics, ecological systems and dynamics, human dimensions of global change, and earth system history and modeling. These papers provide a more complete indication of the range of issues considered by the committee in reaching its conclusions.

Following this Introduction, Chapter 1 of Part I puts forward specific recommendations for the initial U.S. research contributions to the IGBP, based upon the background papers and the committee's analysis of scientific needs and gaps in existing efforts. Chapter 2 discusses supporting needs for program development, including long-term measurements, information systems, and management mechanisms.

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# **PART I**

## **RECOMMENDATIONS**

# 1

## Initial Research Priorities for U.S. Participation in the IGBP

In this chapter, the committee identifies a number of the most critical gaps in our understanding of global change that most urgently need to be addressed in the initial U.S. contributions to the IGBP. The several research initiatives that are recommended in this chapter provide a framework for U.S. contributions to the IGBP in the current planning stage of the program's development. These recommendations are not intended to include all future research needs for the program, but are intended to emphasize those issues not being addressed by ongoing programs.

The committee adopted the following criteria for selecting these initial research initiatives:

- The issue must be global in nature, and research conducted on the topic must be expected to lead rapidly to a greater understanding of global environmental change.
- The magnitude and breadth of the issue must transcend the boundaries of existing research programs and discipline-oriented endeavors, making it unlikely that it can be addressed within traditional disciplinary studies.
- The issue must be amenable to research, with significant progress expected in a period of a few to 10 years or with immediate initiation required in order to build the long-term monitoring and

research base needed for sustained progress in understanding global change.

The research initiatives are recommended on the basis of the committee's systematic review of the current state of knowledge from five perspectives on the earth system: climatic and hydrologic systems, ecological systems and dynamics, biogeochemical dynamics, the human dimension of global change, and earth system history (see the background papers in Part II for detailed discussions). From these analyses—particularly from analysis of the interactions among these five components of the earth system—and from a review of related ongoing programs, the committee identified a number of questions about key relationships that are currently insufficiently understood but essential to improving scientific abilities to predict global change, for example:

- How is the climate system coupled to the dynamics of terrestrial ecosystems, and, specifically, what are the feedbacks between ecosystem dynamics and the hydrologic component of the climate system?
- What factors control fluxes of radiatively active gases between the land and atmosphere and fluxes of biologically important elements from land to aquatic systems? What are the feedbacks between climate change and fluxes of these materials?
- What are the fluxes of biogenic substances from the upper ocean to both the atmosphere and the deep ocean? How do these fluxes affect climate, and how does climate change affect these flux rates?
- How is the coupling of human and environmental systems altered by long-term global trends in social, economic, and technological development? How is the coupling altered by environmental change itself.

#### RESEARCH INITIATIVES FOR EARLY IMPLEMENTATION

Answering these key questions about the earth system demands improved understanding of the influences of terrestrial and oceanic biota on the climate system, and the interactions with the hydrologic cycle, nutrient supply and transport, and surface climate conditions. Answers also depend on an understanding of how anthropogenic activities generate trace gases through changing land use, energy production, and industrial processes.

The committee recommends that these gaps be addressed through major research initiatives on each of the following topics:

- *Water-energy-vegetation interactions*—the coupling between the climate system, especially its hydrological processes, and the dynamics of terrestrial vegetation.
- *Fluxes of radiatively active trace gases and nutrients* to and from the terrestrial biosphere.
- *Biogeochemical dynamics in the ocean* that regulate formation and influence the ocean's capacity to sequester or release radiatively active gases, such as carbon dioxide and organic sulfur species, and their interactions with climate.
- *Earth system history and modeling* to reconstruct the record of the past preserved in ice cores, sediment deposits, and other proxy indicators of change.
- *Human interactions with the global environment* to document and analyze land use changes and changes in industrial production and consumption over the past several hundred years, and to create useful scenarios of future changes in the processes that drive global change.

Issues that need to be addressed in each of these initiatives are discussed below. These discussions, however, only outline the broad initiatives that should be pursued and illustrate the types of experiments, modeling efforts, and observations that will be required. Detailed research plans and schedules must be formulated by groups of experts engaged in the relevant research disciplines.

#### **Water-Energy-Vegetation Interactions**

The committee recommends an observational and research project—a water-energy-vegetation experiment—to study the coupling between the climate system, especially its hydrological processes, and the dynamics of terrestrial vegetation. The initiative has two objectives: (1) to develop validated global models of the response of terrestrial ecosystems to climate, water and land use change, atmospheric chemistry, and other global- or regional-scale stress factors such as changing atmospheric composition, fires, herbivory, and disease; and (2) to determine how ecosystem structure and function affect evapotranspiration, soil moisture, and surface runoff on regional and global scales. The project would in essence be the biological complement to the Global Energy and Water Cycle

Experiment (GEWEX), whose planning is just now beginning under the WCRP.

This research initiative will require field and laboratory experiments, modeling efforts, and observations to address the response of ecosystems to climate changes, as well as the response of climate to ecosystem change. Included would be the following:

- Experiments on whole ecosystems in order to quantify effects of climate change and other stress factors.
- Studies to scale up information on nutrient cycling and plant physiological processes to the level of the whole ecosystem, taking into account the dynamics of key species.
- Recovery of records of past vegetation cover and other indicators suitable for validating the long-term hydrological response of climate models to global change.
- Development of models of global and regional climate that emphasize hydrological and land surface processes (using parameterizations derived and validated by field data and process studies) and that can be used to study the sensitivity of climate processes to vegetation changes.
- Analysis of the human causes and effects of changes in the hydrologic cycle, including documenting past and projecting future human activities important for the hydrologic cycle; defining those aspects of hydrologic change most important for human activities; and developing frameworks for application of hydrologic projections to environmental assessment and management.
- Observations at a global scale of seasonal and interannual variations in vegetation cover and evapotranspiration.

A regional focus to study the coupling between vegetation and the hydrologic cycle in particularly important or sensitive geographic regions such as the Amazon Basin, the taiga-tundra transition zone, and the western United States is an important component of this initiative. Such a focus includes projections of the impacts of changes in terrestrial hydrologic processes on ecosystem composition and functioning in specific regions.

The initiative also requires strong input from other international research programs, such as GEWEX and the International Satellite Land-Surface Climatology Project (ISLSCP), to address the questions of global distributions of rainfall over land and atmospheric properties important for surface evapotranspiration.



### **Fluxes of Radiatively Active Trace Gases and Nutrients to and from the Terrestrial Biosphere**

The committee proposes a research initiative focused on the fluxes of materials such as (1) radiatively active trace gases to and from the terrestrial biosphere, and (2) nutrients from land to aquatic and marine ecosystems.

The objective of a research focus on radiatively active trace gas exchange between the terrestrial biosphere and the atmosphere is to improve understanding of those basic ecosystem processes that determine gas fluxes. This understanding is needed to construct functional models that can be used to predict how climate and land use change will alter emissions and absorption of radiatively active trace gases from the biosphere and, in turn, feed back to further changes in climate. The research should emphasize methane, carbon dioxide, and nitrous oxide, but other significant constituents, e.g., ammonia and organic compounds, are also of concern.

The initiative will require the following:

- Experiments involving plants, soils, and peats to improve understanding of processes affecting gas exchange between them and the atmosphere, such as changes in carbon storage; the influence of nutrient availability; the influence of population dynamics through nitrogen fixation, and microbial processes; hydrological influences on partitioning between production of carbon dioxide and methane and between nitrogen and nitrous oxide; and the influence of the chemistry of precipitation on such processes. Experiments on intact ecosystems that include the biota and soils will also be needed to measure the effect of environmental changes on the complex, interacting processes of vegetation change, nutrient cycling, and gas fluxes. Larger scale ecosystem experiments can involve, for example, manipulations of entire watersheds or can use natural or inadvertent anthropogenically induced perturbations for experiments.
- Investigations at local or regional scales, particularly in ecosystems such as the Arctic and the tropics that play significant roles in global change. A local and regional focus, including comparative studies along environmental gradients, is needed in order to extrapolate predictions of gas emissions to the global scale after a mechanistic understanding of gas emissions is achieved.
- Models that combine descriptions of the functioning of whole ecosystems (process-functional approach) with descriptions of changes in populations and communities within ecosystems (popula-

tion-community approach), in order to predict the changing patterns of fluxes from ecosystems subjected to rapid change. Because this new generation of models will be mechanistic, they could be used to extrapolate beyond existing or past conditions, and to predict gas emissions from new combinations of vegetation, soils, climate, land use, and atmospheric processes.

- Increased attention to documentation of past ecosystems from the record of the past, in order to understand better the range of ecosystem form and function that could develop in the future in response to global change.

- Documentation on a global scale of the history of land uses believed to be sources of methane and other trace gases, and assessments of future changes in human activities that can result in changes in emissions. Similarly, prehistoric and historic activities that have affected carbon storage in vegetation and soils should be documented on a global scale.

The component of this research initiative focused on fluxes of nutrients from terrestrial to aquatic systems will, in addition to studying nutrient transfers in natural ecosystems, emphasize the effects of land use change on the amount and pathways of nutrient losses from terrestrial ecosystems. The objective is to broaden the initiative on trace gas emissions to include analysis of how global changes now under way will affect the transfer of nutrients to riverine, estuarine, and ultimately, ocean systems. As discussed in the following section, changes in ocean productivity have important long-term implications for climate. Thus nutrient transfers from the terrestrial to marine systems could have important feedback effects.

Transfers of materials across ecosystem boundaries will be strongly affected by various aspects of global change. Large-scale experiments, involving manipulations of entire watersheds or intact ecosystems, are needed to assess the effects on nutrient losses of floods, increased fire frequency, loss of species, and other events related to global change. Rising sea level will also affect nutrient cycling and transfer to the ocean. Superimposed on these effects, and in some systems overwhelming them, are massive changes in land use, especially in the tropics, where the human population and activity are growing rapidly. Deforestation and increased intensity of agriculture in dry and humid tropical regions are affecting nutrient availability in soils and transfers to other systems via dust and runoff.

Understanding the processes underlying nutrient losses from terrestrial systems will require monitored watersheds. Once baseline

data are established, experiments with different kinds of land use can be carried out, with paired watersheds left unchanged as controls. These experiments will separate human effects from other aspects of global change. Long-term observations are necessary, as some effects are cumulative and others have long response times. Long-term studies will also increase the opportunity to observe and hence understand unusual climatic events that stress the system.

The important requirements are thus as follows:

- Experimental manipulations of drainage basins to increase understanding of the mechanisms controlling nutrient transfer via water or air from the land to streams, lakes, rivers, and eventually, the ocean.
- Examinations of systems along a gradient, e.g., from savanna to dry forest to rain forest, in order to quantify fluxes as a function of ecosystem type.
- Research to follow the fate of nutrients after they are lost from terrestrial ecosystems into rivers, lakes, groundwater, the ocean, and the atmosphere. Studies of estuarine processing of nutrients loaded into rivers should be emphasized.
- Analysis of the patterns and causes of anthropogenic land use change, including documenting past and projecting future human activities important for terrestrial nutrient fluxes, and defining those aspects of nutrient flux most important for human activities.
- Particular emphasis on phosphorus in nutrient balance studies. While phosphorus is less mobile and dynamic than carbon, nitrogen, and sulfur, it exerts a strong control on productivity both on land and in aquatic systems.

Some approaches appear promising in the context of this research focus. For example, stable isotope signatures of carbon, nitrogen, and sulfur as tracers of element movement and as integrated reflections of the processes controlling element transformation and loss will provide important information. While this approach is relatively well worked out for carbon, considerable development of research techniques is necessary before it can be applied to nitrogen and sulfur. Better measurements of both historic and current rates and types of land conversion also need to be developed and applied.

Collaboration with the research component on fluxes of radiatively active gas, discussed above, is needed to understand, model, and predict biosphere-atmosphere interaction following land clearing.

Additionally, interaction with ongoing programs such as the International Union of Biological Science's Tropical Biology and Fertility Program and the International Atomic Energy Association-Centro Energia Nuclear na Agricultura (IAEA-CENA) Amazonia I Project will be needed for the research focus discussed here.

The overall initiative should be linked with activities of experts concerned with land use change as a primary driving force in species extinctions worldwide (see "Human Interactions" initiative below). Both the information on rates of land use change and the measurements of the fate of nutrients once they are lost from cleared land are fundamental to these efforts, and knowledge of the functional significance of particular species in local areas is fundamental to this initiative.

### **Biogeochemical Dynamics in the Ocean**

The committee recommends a research initiative to understand and predict the effects of climate change on ocean biogeochemical cycles and their corresponding feedback to climate. The objective of this effort is to develop the capability to predict the effect of projected global climate change on the ocean's physical/chemical and biogeochemical processes, especially as they feed back to climate via the release or absorption of radiatively important gases such as carbon dioxide and organic sulfur species.

Changes in climate over the ocean will alter the physical conditions of the upper ocean. Incident irradiation, evaporation/precipitation, and wind shears on the ocean surface help to define the mixing state, and hence the nutrient supply and residence time for plankton. Nutrient supply and re-suspension properties are important factors in determining the nature of the planktonic food web. Greater rates of nutrient supply, and higher mixing rates, for example, promote the growth of large diatoms. These two different types of plankton sustain markedly different food webs and have significantly different consequences for the residence time of photosynthetically fixed carbon in the ocean. In addition, different plankton groups have different physiologies related to sulfur metabolism and play considerably different roles in the evolution of organic sulfur species, which have climatic implications when liberated to the atmosphere.

This effort will require a global-scale assessment of the processes governing the rates of primary production and determining the fate of biogenic materials in the sea. A major international program, the

Joint Global Ocean Flux Study (JGOFS) is now being defined in this area. It will consist of global observations, regional process studies, coastal ocean studies, and modeling. Some of the recommendations below will probably be included in JGOFS, some should be initiated as soon as possible, while other activities, especially those related to the biogeochemical implications of the anticipated climate change, may require results of JGOFS and other ocean programs such as the World Ocean Circulation Experiment before they can be initiated.

A U.S. contribution in this area should include the following:

- Helping to establish the global remote sensing capability and appropriate sea surface verification necessary to assess temporal and spatial patterns in plankton distribution.
- Studying the processes responsible for the initiation of plankton blooms (including dependence on temperature, mixing state, and nutrient supply) and their roles in (1) the flux of organic material and calcium carbonate to the deep sea and (2) the production of organic sulfur compounds, which, when liberated to the atmosphere, have implications for climate.
- Developing modeling and scaling techniques to generalize the results of intensive local studies of plankton blooms to characteristic regional and basin scales.
- Placing emphasis on those high-latitude ocean regions where vertical fluxes of carbon to the deep sea and vertical fluxes of nutrients to the surface waters give these regions disproportionately large global significance.
- Investigating the biogeochemical processes responsible for forming, transporting, and preserving in ocean sediments the hard parts of plankton used in studies of past climates.
- Initiating large-scale models of upper ocean physical and biogeochemical processes that can be used to assess the effects of climate change on biogeochemical processes that have potential to feed back to climate via the regulation of radiatively active trace gas release from the ocean.

### **Human Interactions with Global Change**

This research initiative would focus on the relatively short-term record of the period of intensive human activities that have affected the global environment. Anthropogenic changes in the earth system need to be systematically documented over the past several hundred years and analyzed as a basis for developing useful reference scenarios

of future change. In particular, two aspects of human activity are especially relevant to global change: land use changes, which influence both physical (e.g., albedo, evapotranspiration, and trace gas flux) and biological (e.g., vegetative cover and biodiversity) variables; and the industrial metabolism that transforms resources into emissions that must be absorbed and processed by the environment.

Investigation of global land use patterns would involve the following:

- Construction of a core conceptual model or theory of the causal relations underlying changes in culture (e.g., population, development values) on one hand and changes in environment on the other hand, to human choices that affect long-term, large-scale patterns in the use of land.
- Documentation of how key variables of land use, population, agricultural prices, and so on, identified in the conceptual model have changed throughout the world over the last several hundred years.
- In-depth regional case studies of the general relationships suggested in the conceptual and historical work.
- Construction of future scenarios of global land use change, and exploration of how alternative human choices regarding global change could alter those scenarios.

Parallel to the study of global land use change, a similar approach to the study of industrial metabolism would involve the following:

- Construction of a conceptual model linking demographic, economic, and institutional factors with the evolution of material and energy uses, and human consumption processes relevant to global change.
- Documentation of how particular material and energy resources have been metabolized through human production and consumption processes over periods of decades to centuries.
- In-depth regional case studies of the general relationships developed in the conceptual and historical work.
- Construction of future scenarios of industrial metabolism and associated materials and energy exchanges with the environment.

### **Earth System History and Modeling**

The initiative on earth system history and modeling is concerned with documenting and understanding overall patterns of global change. The initiative would focus on reconstructing the past

over tens of thousands of years to provide a data base for validating global change models. The history of atmospheric composition and climate, and of the spatial distribution of climate, vegetation, and ocean circulation would be developed. Special attention is needed on periods of rapid change to provide insight into poorly understood system processes.

A research focus on the long-term record requires the following:

- Data from polar and temperate latitude ice cores, ocean sediments and corals with 10- to 100-year temporal resolution, and various kinds of physical and biological terrestrial records.
- Theoretical studies and modeling to establish quantitative relationships between measured parameters and physical processes, in order to better interpret the record of the past.
- Sensitivity studies with global models to define the spatial and temporal resolution needed in the study of the record of the past and to suggest which types of data should be collected.
- Development and improvement of global change models based on observations from the record of the past. Models can use information from the past record such as climate and vegetation and indirect measures of the carbon cycle. Past abundance of carbon dioxide, methane, carbon-13 and other stable isotopes, and other chemical species accessible from the record can be used for model validation. Data on the history of human interactions with the earth system, as developed in the previous initiative, will also be useful. Close collaboration between observational and modeling activities is essential.

#### DEVELOPMENT OF RESEARCH INITIATIVES

Two streams of activity are required to develop the research initiatives for the U.S. contribution to the IGBP into detailed plans for research programs: (1) involvement of scientists with particular expertise to develop the research plans, and (2) support of those related activities essential to the success of the IGBP.

Steering groups should be established on each of the five research initiatives proposed above as research foci for the initial contribution to the IGBP. These groups should be closely coordinated with other relevant activities in the National Research Council. These steering groups, operating under the Committee on Global Change over approximately the next two years, would engage scientists with the relevant expertise to further define programs of coordinated research

in the respective area. The Committee on Global Change would ensure that the research plans developed by each group are coordinated into an overall plan for the U.S. contribution to the IGBP.

Support for existing programs related to the goals for the IGBP is also an integral part of the U.S. effort. Three categories of support can be identified:

1. As noted above, U.S. contributions to the IGBP are drawn from the broad suite of U.S. observational and research programs that have been described as the U.S. effort on global change. The U.S. program is based on the concept developed in the report of the NASA-sponsored Earth System Sciences Committee that study of the earth as an integrated system is an important and timely paradigm for the earth sciences. Strong support for such a broad national effort in the study of the earth is an essential foundation for the focused programs addressed in this report.

2. A number of existing, ongoing programs have objectives and well-developed plans that clearly fall entirely or partly within the scope of the IGBP or the broader U.S. global change efforts. Among these are UNESCO's Man and the Biosphere Program, the several projects of the Scientific Committee on Problems of the Environment related to global change, and the United Nations Environment Program's Global Environmental Monitoring System (GEMS). Particularly relevant and essential are the components of the World Climate Program. One of these, the World Climate Research Program, organized under the World Meteorological Organization (WMO) and ICSU, focuses on dynamic and hydrological processes in the climate system and has in planning or in progress a number of well-conceived projects (e.g., Global Energy and Water Cycle Experiment, World Ocean Circulation Experiment, Tropical Ocean/Global Atmosphere Program, International Satellite Cloud Climatology Project, and International Satellite Land-Surface Climatology Project) that promise to contribute greatly to the goals of the IGBP. The contributions of the Data, Applications, and Impacts components of the World Climate Program should also be emphasized. The IGBP and these existing activities are highly complementary and mutually supportive.

The challenge is to harmonize and coordinate the practical work of the various planning bodies so that each activity can be effectively focused on appropriate objectives. Such an approach was successfully employed in the Global Atmospheric Research Program (GARP), where the WMO/ICSU Joint Organizing Committee, the



ICSU Committee on Space Research, the International Association of Meteorology and Atmospheric Physics' (IAMAP) Radiation Commission, and other bodies pursued closely coordinated programs. Interaction within this family of closely related activities in the earth sciences should be strengthened, coordinated, and enhanced.

3. Support for discipline-oriented research related to the goals of the IGBP is needed to bolster the scientific foundations of the program. For research centered on the atmospheric and oceanic components, a long and mature history of previous studies and an array of coordinated research programs provide good foundations for contributions to the understanding of global change. In other areas, such as the biological and human components of global change, the existing research program is less well developed. The relevant research communities should be encouraged to develop their own internally justified research priorities relevant to global change. An aggressive program to support research in these as well as other related disciplines is needed.

For instance, a number of areas of needed research are highlighted in the background paper on ecological systems and dynamics (see especially the section on principal issues and research challenges). These include (1) research on physiological responses of plants and animals to the environment, especially to multiple stresses; patterns of genetic variability, including the development of theory regarding evolutionary responses to rapid environmental change; the direct effects of elevated carbon dioxide concentrations on intact ecosystems; and characteristics that allow some species to adjust geographical ranges rapidly in the face of change while others become extinct; (2) monitoring of ongoing changes in distributions that may record the incipient effects of global change and of ongoing changes in land use; and (3) development of more complete paleorecords, particularly from little-explored parts of the earth.

The existing research program on the human components of global change is also inadequately developed, as discussed in the background paper on the human dimension. Efforts to bring together natural, social, behavioral, and engineering scientists to examine in-depth the research required on the human dimension of global change should be supported. Several research areas identified in the background paper—integrated methods to assess the risk and implications of long-term environmental change for resource availability at the regional scale; ways that knowledge, perceptions, and values related to global change can be more effectively brought to

bear on human choices that affect global change; and evaluation and design of institutional mechanisms for better management of global change—require further development in close collaboration with those relevant scientific communities in the social, behavioral, and engineering sciences that were not adequately represented in current planning activities.

## 2

# Supporting Needs for Program Development

Planning of the IGBP will have to be responsive to a number of challenges that transcend previous experience with collaborative scientific programs. These challenges are presented by the exceedingly broad scope of the program, the need to blend new technology with traditional observational techniques on a worldwide scale, the need to plan and sustain a coordinated research and documentation effort over many decades, and the need to present to the public and policymakers in a timely and comprehensible manner the conclusions on complex issues of substantial and growing public concern.

A number of common themes should guide the development of specific plans for research and observations to be carried out as part of the IGBP:

- *Documentation of significant contemporary changes in the global environment requires establishment and maintenance of long-term observations.* Long time-series measurements of key variables, such as global trends of trace gases and global changes in land use, are needed to detect global changes. Monitoring of sensitive ecosystems for critical parameters, such as productivity and species loss, can provide early warning signals of global change. In addition, such long-term records often provide unanticipated insights into system dynamics. The careful design, implementation, and application of long-term observations and associated information management sys-

tems will be a critical element in global change research.

- *The need for recognition of the significance of discontinuous and extreme events in the earth system* (e.g., periods of extreme temperature, droughts, hurricanes and flash floods, and plankton blooms). The research and observational programs should include the capacity to act rapidly to investigate the response of the system to any such events. The program should also be designed to recognize that changes in the frequencies of extreme events might indicate the occurrence of fundamental changes in the earth system.

- *The identification and investigation of particular ecosystems* that are most subject to change and/or that have particularly strong potential for feedbacks to the physical climate system. For example, global warming may increase dramatically rates of metabolism in arctic tundra, with currently unpredictable consequences for release of methane from thawing permafrost. The high biodiversity in the tropics and the significant role that the tropics play in the earth system make these areas important for global change research. In addition, ecosystems receiving high anthropogenic inputs of nutrients, arid zones, agricultural systems, and ecotones or transition zones that are anticipated to be sensitive indicators of global environmental change are areas deserving intensive investigation. A focus in the IGBP on such geographic areas would provide a focus for research and would permit efficiency in collection of data.

### DOCUMENTING GLOBAL CHANGE

At the core of the IGBP must be a systematic effort to document the significant changes on a global scale over the coming decades. This effort overlaps, but is distinct from, research initiatives aimed at elucidating key processes involved in such changes and efforts to examine the record of the past. All these activities are necessary to develop and test quantitative models of how the entire earth system functions on time scales of decades to centuries. The program structure and institutional arrangements must be appropriate in order to (1) obtain the necessary observations and calibrations, (2) process and analyze them to extract the required information, and (3) assemble this information and make it accessible to scientists and policymakers worldwide and to future generations.

### The Role of Models

Because of the complexity of the interactions between different parts of the earth system, a central goal is to codify understanding of specific processes and measurements of large-scale changes in terms of quantitative models. To the extent that credible models based upon established principles can be developed and verified against an adequate base of observations, they can then serve as testbeds for evaluating hypotheses about cause-and-effect relationships and for development of efficient observational strategies, and for deriving predictions about future trends. Models are discussed in more detail in the background papers in Part II of this report and in the report of NASA's Earth System Sciences Committee (1988). Here it suffices to abstract some general concepts.

Comprehensive quantitative models of the earth system are formulated in terms of a set of state variables, such as the temperature distribution in the ocean or the concentration of nitrous oxide in the atmosphere. These state variables are on a global scale and are inevitably simplified idealizations of reality. Their development with time is defined by predictive equations or algorithms that codify our understanding of the specific processes that connect them. Enhanced understanding resulting from process studies becomes reflected in improved algorithms in such models. Documentation of global change, on the other hand, implies determination of the time history of the state variables themselves. Establishing confidence in a model requires a rigorous process both of assessment of its basic principles in the light of accumulated understanding of the processes involved, and of testing its parts and the entire model against measurements of the state variables. Because of the empirical idealizations involved in constructing a practical model, substantial redundancy is required in such tests. In general, the greater the ability of the model to simulate observed behaviors on increasingly longer time scales or changes that are independent of the information invoked in its development, the greater the confidence in its predictive capability.

Thus a research and measurement strategy aimed at using models as the primary integrating tool would concentrate on two rather distinct activities: (1) focused studies enhancing understanding of selected processes and (2) long-term global measurements of key state variables.

### Process Studies

Scientific research organized into process studies need not necessarily be global and should normally be of limited duration, resulting in improved algorithms through which their conclusions are applied on a global scale. The emphasis is likely to be on simultaneous intensive observation and measurement of a wide variety of variables in a few case studies, using any available techniques including experimental ones. The choice of variables and techniques will derive from the specific experimental design for each study and may change with increasing understanding of the process. Diverse analysis procedures will be used by individual scientists to contribute to a collective understanding that is then distilled into algorithmic form.

### Long-term Measurements

Long-term measurements of state variables, on the other hand, must be global and sustained at acceptable quality for many decades. The observation and analysis techniques must be standardized and applied systematically and cost effectively in a manner that is frequently described as routine or operational. It should be noted that the term "measurement" is used to include here all aspects of the inferential chain from the original observations to global analyzed products, and it is essential to consider the entire system. Many factors affect the end-to-end performance of this system, including the calibration of the original sensors and other data sources and the coverage in space and time. Validation of the inferential process connecting the sensor output with the variable being analyzed and the algorithm being used to implement that connection also affects the end-to-end performance. Procedures for quality control and editing of the data for global analyses, and the availability of independent measurements that can be used, at least on a spot basis, to compare with the routine output cannot be overlooked. A final factor critically important to global change is the documentation of all these items in a manner that will enable scientists 20 years from now to determine whether observed changes are real or merely artifacts of the way the measurements were made or interpreted.

Difficult though it may be to sustain such measurements, documenting global change requires that they be sufficiently comprehensive both to enable the causes of observed changes to be inferred

from model simulations and to use available models to test alternative hypotheses for the causes of observed changes. To the extent that established models exist, the required set of ongoing measurements can be reduced somewhat by utilizing implied relationships between state variables (for example, the geostrophic relation between wind and pressure in the extratropical atmosphere). For some variables, such as the solar irradiance or the concentration of carbon dioxide in the atmosphere, the small spatial variability is such that a few sustained measurements of high quality suffice for the most important information on a global scale. For other variables, such as temperature, we must rely on an extensive network of observations and international data exchange maintained for other purposes. For yet others, such as precipitation or subsurface ocean circulation, acceptable techniques applicable routinely on a global scale do not yet exist, and a research and development effort is called for to enable the most critically important gaps to be filled. For still others, a network of surface observations such as the proposed International Geosphere-Biosphere Research and Training Centers discussed below would seem most appropriate at this time.

It must be recognized that documenting global change through long-term measurements presents an organizational, managerial, and technical challenge and political commitment of profound importance. Resource limitations will certainly require full collaboration with existing organizations collecting relevant data for other purposes (such as weather prediction). New mechanisms will have to be established to identify cost-effective ways to supplement these systems to make them useful for long-term measurements. Remote sensing from space is a powerful tool for obtaining global observations, but in most cases the data must be combined with in situ measurements from other sources in a composite observing system for a fully satisfactory analysis. Mechanisms must be established to review the end-to-end performance of such composite systems and to make necessary adjustments (see the discussion on information systems below). In some areas, pioneered by the weather services of the world and the World Climate Research Program, observational networks of considerable maturity are in routine operation. In most areas, however, the infrastructure for coordinated planning of in situ and remote observations, international data exchange, analyses, and validation of end-to-end performance will need significant strengthening.

### Data from the Past

Because the time scale for global change is comparable to the time over which research in the IGBP will be conducted, concentrating on the present and future behavior of the system is insufficient. It is necessary to seek independent data sets for model testing and evaluation in the record of the past, in spite of the loss of precision that may accompany the use of proxy data or incomplete records. Emphasis should be placed on circumstances most likely to yield relatively complete data sets useful for testing at least some aspects of quantitative models, or on determining the natural variability of individual key state variables. Because only part of the desirable information is available, in some cases only in principle, choices in research strategy derive primarily from the development and application of techniques to infer global-scale variables from limited, often indirect, data. Because knowledgeable judgments are required at so many stages, reconstructions of past states of the earth system will never become routine inferences from a predefined observation system. The research and information management structures in IGBP should reflect the inherent characteristics of preinstrumental data.

### Additional Comments

The conceptual distinctions made above between process studies, ongoing measurements, and earth history provide broad indications of the range of IGBP activities and as such may assist in defining programmatic structure for a measurement strategy, but they should not be regarded as rigid prescriptions. For example, the first three of the initial foci recommended in Chapter 1 involve a mix of process studies and activities aimed at developing the capability for long-term measurements, and studies of the human dimension, aspects of which may defy simple algorithmic treatment.

Furthermore, the status of our comprehensive models is such that they are currently at best only partially useful for setting requirements for long-term observation and analysis systems. Indeed, there is no accepted model in existence that covers the full range of interactions between the physical, chemical, biological, and human subsystems of concern to IGBP. In some areas of concern, such as terrestrial ecosystem dynamics, there is inadequate understanding of the basic principles for constructing a model to operate on a regional scale, and hence no consensus on what the principal state variables should be, let alone consensus on the algorithms connecting them.



Almost all our current models are vulnerable to the total omission of processes that may turn out to be of major importance. For example, recent discoveries suggest that heterogeneous chemistry in ice clouds is central to the control of ozone in the antarctic stratosphere, although previous models were restricted to gas phase interactions. Thus, as our understanding of the interactions within the earth system improves, perceptions of the relative importance of different state variables as key indicators of global change are likely to be adjusted also. Meanwhile, our best judgment must be the basis for action in obtaining at least a minimal set of such indicators.

### **MEASUREMENT STRATEGY**

#### **Implementation of Long-term Space-based and In Situ Measurements**

The list of potentially important long-term global measurements is long and has not yet been reviewed in detail by this committee. Careful consideration will have to be given to the selection of the most critical variables for special attention, particularly in relation to the end-to-end performance attainable by augmenting existing data gathering and analysis activities, both remote sensing and in situ, and in relation to the potential for development of new techniques suitable for global deployment.

Both satellite- and ground-based measurements will provide essential information for the IGBP, and the measurement strategy needs to be designed so that one complements the strengths and weaknesses of the other. Satellites provide global coverage and frequent and long-term observations, but currently provide only qualitative information. Several parameters important to the IGBP cannot, with current technology, be measured from space (e.g., precipitation, soil moisture, gas fluxes, winds, and tropospheric chemistry). In situ measurements, on the other hand, provide potentially accurate measurements of many variables important to the IGBP and are essential to validation of space-based observations. Clearly, however, surface networks cannot realistically provide global coverage on a long-term basis.

Meanwhile, it is clear that the capability for long-term measurements can be developed most effectively in the context of specific research foci that need them, at least in the short term. In this context, programs such as the Tropical Ocean and Global Atmosphere program, the Global Tropospheric Chemistry Program, the

World Ocean Circulation Experiment, and the Global Energy and Water Cycle Experiment of the World Climate Research Program are not only essential process studies, but also critically important environments for the evolution of our ability to document global change. Satellite missions approved for deployment in the near future, such as UARS, ERS-1, TOPEX/Poseidon, and Sea-WIFS aboard Landsat-6 will each contribute major new types of measurement on a global scale, from which could evolve an effective long-term capability for very important global state variables. New applications of existing data streams, such as the Vegetation Index recently developed from the AVHRR sensors aboard NOAA polar orbiters, can be highly effective although relatively inexpensive.

*The committee recommends that planning continue vigorously for the deployment in the mid-1990s of a more comprehensive long-term interagency and international Earth Observing System, with major components aboard a number of polar-orbiting platforms, supplemented by particular instruments in tropical and geostationary orbits, and building upon existing, ongoing research and operational observing programs. Special attention should be given to the integration of the space-derived data from EOS with complementary in situ data and validation studies to derive long-term analyzed global products containing documented information. Specific sites for validation studies need to be established.*

#### **International Geosphere-Biosphere Research and Training Centers**

*The committee recommends that a limited number of International Geosphere-Biosphere Research and Training Centers be established to provide bases for research and observations of global change. Many of the planning reports for the IGBP have recommended the establishment of geo-biosphere observatories, which would serve many important functions related to global change research. Observatories have been recommended as sites for long-term observations, process studies including large-scale manipulations of ecosystems, training, ground truth validation for remote sensing missions, model validation, and other purposes. The multiple utility of observatories is compelling, and research related to long time series of observations would benefit from institutional mechanisms to coordinate observatories.*

A hierarchical approach to the concept of biosphere observatories should be employed. At the base of the hierarchy would be the extensive, existing net of specialized monitoring and field stations, supplemented where necessary by new installations in sparsely represented areas. At the middle of the hierarchy would be sites already established for long-term research, such as biosphere reserves of UNESCO's Man and the Biosphere Program and the U.S. Long-Term Ecological Research sites maintained by the National Science Foundation. Again, this mid-level could be strengthened where appropriate with new facilities. At the top of the hierarchy would be a limited number—perhaps half a dozen—of new International Geosphere-Biosphere Research and Training Centers established to realize the goals of the IGBP.

Possible research foci for these centers are the roles of tundra, tropical, semiarid, temperate forest, and high-latitude ocean systems in global change. Sites for the centers would be selected on the basis of ecological characteristics, geomorphology, human factors, and potential for climate change.

The primary purpose of the centers would be to serve as major foci for international cooperation in research and training by (1) providing a base for large-scale manipulative experiments designed to understand linkages between ecosystems and climate change, (2) developing efficient hierarchical networking with other international and national research and observational programs and organizations, such as designated ecological research sites and reserves, (3) orchestrating the development of facilities for smaller scale and more transient observational and process studies, (4) serving as a central repository for detailed observational and experimental results on the systems represented by the respective center, and (5) constituting a tangible international commitment to continuing cooperative efforts to understand global change.

To be successful, the centers would have to be developed in accord with the ICSU practices for full access for scientists from all nations. It would be essential that leading scientists spend significant blocks of time in residence in order to facilitate training of students and young scientists in global change research. Moreover, the success of this effort would require commitment of funds from all nations, regardless of the suitability of their own territories for the siting of a center.

## INFORMATION SYSTEMS

Global change must be documented consistently over many decades, across disciplinary and international boundaries, through evolving perceptions of what is most important, and under pressure from governments and citizens to provide as soon as possible reliable information about what are expected to be ever increasing concerns to the peoples of the world. The system by which irreplaceable data are made accessible to all who need them and are preserved for future generations is the foundation on which the enterprise must be built. It is also the component of the program that experience shows is most likely to founder through ineptitude or neglect.

Perhaps even more important than the primary data is the distillation into derived products or analyses of lower volume but greater information density, which in turn are used as data for model development or cross-disciplinary studies that yield information about the functioning of the earth system. It is thus essential to extend traditional concepts of data management to include the recapture and preservation of these derived products and the means to make them accessible to a group of users who may not be familiar on a day-to-day basis with all the details of the original data stream. The sheer volume and complexity of primary data relevant to global change enforce utilization wherever possible of higher level syntheses or abstractions that have already been made by some other competent user. In other words, the data management system must become a complete information service.

These requirements pose major technical, institutional, and managerial challenges to our existing structures. For example, an unfortunate byproduct of the explosion over recent decades of digital data and techniques for handling them has often been the separation of the data themselves from metadata, or information about the data. This is because metadata are generally in text or graphical format that does not easily fit into efficient database management structures or standardized tape formats. Yet information about the algorithms used for a derived product, the quality control procedures, comparisons with independent measurements, reviews by expert outsiders, and so on, is what enables the user to judge the reliability or value of the product for a particular application, and should therefore be an inseparable part of the data set. The same is also true for original data in terms of calibrations, quality control flags, and so on. With more powerful computers and software systems the storage of

metadata should not be a fundamental limitation. However, a major effort is needed to develop standards for the exchange of entire data sets including metadata between data centers. A similar effort is needed to enable electronic distribution of catalog and directory information. Other issues arise from the diverse and untraditional sources of derived products, and the need for mechanisms to select the most significant products. However, new opportunities are also provided by technological developments such as the advent of digital publishing on CD-ROM and similar media.

The IGBP can draw upon a number of existing institutional mechanisms for data exchange between nations. The World Data Centers were established during the IGY as central repositories from which contributed scientific data could be made available to participating nations. Frequently co-located with a national data center in the host country, WDCs have proved a valuable mechanism for international data exchange within a number of the disciplines involved in the IGBP. However, the volume and complexity of even present conventional data streams from in situ sensors are severely taxing the available capabilities, and major upgrades will be necessary to meet the information needs of the coming decades.

In addition to the WDCs, there are operational exchange mechanisms in disciplinary areas for specific purposes that overlap with IGBP requirements, for example, the real-time exchange of meteorological and ocean surface layer data over the WMO Global Telecommunications System for use in weather prediction. The distribution channels for satellite data have evolved along separate lines, partially conditioned by the large data volumes typically involved and the need for timeliness. Under the open skies policy enunciated by the United States, image data from U.S. weather and Landsat satellites are directly available to any nation installing the necessary ground receiving equipment. However, with the more specialized, high-data-rate instruments of the future, the raw data are best processed in one location. Rebroadcast of results of analyses is a more complex operation. In addition, an ever-increasing number of nations or space agencies are now operating or plan to operate satellites that can potentially make important contributions to IGBP, but not all of these have made clear commitments to an open skies policy. For research satellites, premature dissemination of the data is clearly inappropriate, and access is usually initially limited to specific investigator teams. Subsequent access by scientists from other countries has tended to be ad hoc, on the basis of bilateral arrangements.

These considerations require that urgent attention be given to identifying criteria that separate bona fide applications of satellite and relevant in situ data to the study of global change from uses with commercial, national security, or proprietary interests. Effective mechanisms for truly international exchange of such data need to be established, at least for the purposes of IGBP. Ill-considered proliferation of ad hoc bilateral arrangements risks dividing the scientists of the world into those in nations that have access to essential global data sets and those who have to be content with secondary sources of unverifiable quality, with serious consequences for international collaboration and the credibility of research results from the program.

The evolution of a practical and effective information system will be facilitated by a combination of a top-down and a bottom-up approach. A top-down consideration of the entire system should include the end-to-end performance requirements for long-term measurements. The special needs of data from process studies at specific sites and investigations of global history, as well as possible institutional arrangements for international exchange of all types of data, need to be considered. A bottom-up approach aims at establishing on an experimental basis role models of effective solutions to a much more restricted set of problems.

In the latter context, *the committee recommends that a Global Information System Test be implemented to test the end-to-end performance of an early prototype of an information system for the IGBP.* This test would be implemented in 1992 or soon thereafter, possibly in association with the International Space Year. Its objectives would be to make selected satellite and related data sets accessible to an international group of scientists and to document the information content of associated derived products. This end-to-end test would be conducted in the context of recognized research foci within the IGBP or in the WCRP that would serve as a prototype. A limited number of variables would be selected on the basis of scientific need, the availability of the necessary data, the effort required, the potential to test significant aspects of the data and information system, and the availability of a group of scientists and data professionals committed to making it a success. Such a test could be an important learning experience for the implementation of the Earth Observing System and related activities later in the decade.

## MANAGEMENT OF THE IGBP

The scale and number of interested parties in IGBP focus attention on the effectiveness of existing institutional structures at both the national and the international levels. These structures include nongovernmental scientific organizations like ICSU and COSPAR; intergovernmental organizations like WMO, UNEP, and IOC; individual universities; consortia of universities; and federal laboratories. The structures in place have proven partially successful for the focused programs of the past, but are untested for the broad and multidisciplinary programs of the future. It is not clear that entirely new structures will be required; however, success for the IGBP demands at the very least much stronger coordination among existing organizations and mechanisms.

The program, if successful, will be complex, will cross most national boundaries, will involve many disciplines including the social sciences and engineering, will require a blending of high technology with traditional techniques, and will develop a new kind of real-time information system linking research and operations. Implementation of these plans will require a high order of management skills and mechanisms. Formulation of public policy will be a logical complement to the science aspects of the program, and care must be taken to assure that the two aspects freely trade information.

### A Brief History

The International Geophysical Year, Global Atmospheric Research Program (GARP), and World Climate Research Program (WCRP) are often cited as models of institutional arrangements that give guidance to the IGBP. Each of these has laid groundwork for the next. IGY, essentially the aggregate of research by individual investigators and national teams, provided international access to data through the innovative concept of World Data Centers. Coordination was accomplished through a small committee of ICSU augmented by an advisory council of designated representatives from participating countries. The satellite programs were national contributions (Bullis, 1973). World Data Centers in the context of new technology will be an important aspect of the IGBP.

The Global Atmospheric Research Program was more complex. An intergovernmental mechanism already in place was used to coordinate meteorological satellites. A formal treaty was drawn up between ICSU and the World Meteorological Organization to ensure

strong scientific guidance and participation together with the management capability of an operational agency. These are the kinds of linkages that will be required, but on a much larger scale for the successful operation of an IGBP.

The World Climate Research Program involves atmospheric science, oceanography, and land surface processes. Here the WMO/ICSU links have been augmented by new arrangements between the ICSU Scientific Committee on Oceanic Research and the Intergovernmental Oceanographic Commission. The International Association of Meteorology and Atmospheric Physics (IAMAP) and International Association of Hydrological Sciences (IAHS) have been involved in land surface studies. U.N. agencies such as United Nations Environment Program (UNEP) are involved in the program as well. The inclusion of a larger number of agencies and links than was the case for GARP has been necessary for the program; however, at the same time the management has become more cumbersome.

### An Emerging Concern

The need for examination of existing international institutional arrangements does not derive solely from the IGBP, but rather has been a concern for several years. In 1985, two meetings were held on this subject. Both existing and new models for facilitating international cooperation were considered (Kendrew et al., 1986; Kohn et al., 1987).

The U.S. House of Representatives (Fuqua, 1986) concluded that science could be used to move nations beyond the realization of individual national goals to the next level of global needs. The report noted the need for an international cooperative science decision-making mechanism beyond what now exists. The International Institute for Environment and Development and the World Resources Institute (1987) observed that an understanding of global change is driven by forces that call for a reorganization of science to study the earth as a planet.

The World Commission on Environment and Development (1987) concluded that global environmental and developmental problems are inseparable and that they must be approached in a holistic manner. The commission believed that the actions required for success are beyond the reach of present decision-making structures and institutional arrangements, both national and international.



### The Need for Reexamination

The IGBP creates a specific and clear need for a careful examination of our existing national and international mechanisms and arrangements. In summary, there are three reasons why international institutional arrangements need to be reexamined:

1. IGBP will be global and multidisciplinary. On the nongovernmental side, ICSU is also global and multidisciplinary. Therefore ICSU is the proper international scientific organization for scientific guidance of IGBP. On the governmental side, there is no one agency that has the capacity to mobilize the operational capability for observations and data management, to cover all relevant disciplines, and to represent all nations. A coalition of operational agencies will be required.

2. The space component of the global observing system will be more cost-effective and better able to distribute data widely if it is fully internationalized. There are existing groups, but they need closer coordination. These include the International Polar-Orbiting Meteorological Satellite (IPOMS) Group, the Coordination of Geostationary Meteorological Satellites (CGMS) Group, the Committee on Earth Observations Satellites (CEOS), the International Forum on Earth Observations using Space Station Elements (IFEOS), and the Coordination Group of Space Station Partners on the Use of Polar Platforms for Earth Observations. These are all groups that offer opportunity for international dialogue among representatives of earth observation agencies. Regional groups of other countries, such as the Society of Latin American Specialists in Remote Sensing and the Asian Society for Remote Sensing, also exist. On the nongovernmental side, we can look to COSPAR for coordination and guidance.

3. An information system that would provide all researchers with access to data on the time scales required for both operations and research clearly requires close communications, and technology has outstripped current international institutional capability. We must preserve the archiving and access availability, especially for developing countries, to data about the earth, while at the same time using the latest technology to make the data system effective and comprehensive.

The urgency of establishing a program does not mean that every detail must be put into place at once. The immediate need is to ensure that the international structure is adequate to cope with

the broad issues of multidisciplinary science using high-technology observational and modeling instrumentation and computers.

It is clear that international institutional arrangements for IGBP need to be addressed soon, so that any proposed changes in existing structures can be fully examined by all the relevant and interested parties. It is also clear that the developing history of the study of the earth has given the scientific community both significant experience in learning how to work together in an interdisciplinary mode and a rich "bag of tools" for management and administration.

Although the structures in place are untested for the broad and multidisciplinary programs of the future, it is not clear that entirely new structures will be required for the IGBP. However, success for the IGBP demands at the very least much stronger coordination among and strengthening of existing organizations and mechanisms. The preferable mode of management is one that requires the least change or addition to existing mechanisms, but the need for new institutional structures should not be ruled out, provided that the necessary coordination and guidance are made available.

*The committee recommends that ICSU convene an impartial group of experts in the near future to develop specific recommendations to the international community on organization and management of the IGBP.* This group should include representatives from the existing large programs such as UNESCO's Man and the Biosphere Program and WCRP, as well as from the program areas to be emphasized in IGBP.

### National Organization

At the national level, there is a need for fostering interdisciplinary programs on global change in universities and in private and federal laboratories. A number of these are already in place, and it may well be that there is an important role for activities sponsored by university consortia. Universities make up the most central, pervasive, and stable infrastructure to provide the needed knowledge base, to develop the global model components, and of course, to educate an appropriate and adequate talent base to pursue the quest of understanding the earth system in the coming decades. Substantial research expertise also exists in a variety of industrial and nonprofit laboratories, which can offer specialized capabilities not available in university or federal laboratories.

The specific activities to be undertaken will depend on scientific

priorities, which in turn will come from the scientific communities involved. The federal laboratories constitute a major national resource for global change research. Particularly, these laboratories are often the managers of and participants in large-scale, complex research programs involving ships, aircraft, rockets, spacecraft, ground-based research facilities, and global-scale measurement networks. They are also frequently among the first recipients of advanced computers, and thus, in many research fields, have forefront and extensive computational capabilities. Several federal laboratories are leaders in the development of global models for atmospheric, oceanic, and land processes, and are repositories for global-scale data bases. The federal laboratories are encouraged to strengthen their interdisciplinary and interagency programs in global change research, and to increase their interactions with university researchers and students to enhance effective use of these extensive national resources for research on global environmental change.

It is clear that the breadth and scope of the IGBP necessarily involve the efforts on many federal agencies with diverse missions, capabilities, and constituencies. Harmonious working relationships and effective coordination will be essential to optimize U.S. contributions. Coordination at the agency level is already being addressed through the FCCSET Committee on Earth Sciences (CES).

The Committee on Earth Sciences effectively represents the federal agencies with major interest in global change and has proved to be a useful forum for airing planning issues. The full cooperation of the agencies involved in CES will be important for the success of the U.S. contribution to the IGBP. It will also be essential that CES work closely with the Office of Management and Budget since the recommendations will cut across many agencies and will have budgetary implications for all agencies.

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PART II  
BACKGROUND PAPERS

# Biogeochemical Dynamics

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## UNDERSTANDING THE ROLE OF BIOGEOCHEMICAL DYNAMICS IN GLOBAL CHANGE

With hydrogen and oxygen, four elements—carbon, nitrogen, sulfur, and phosphorus—are of particular interest in the study of our planet. Through the active intervention of the biota, each of these four elements follows a closed loop or cycle, passing through molecular species of increasing energy content as the elements are incorporated into living tissue, and then moving through decreasing energy levels as the organic matter is returned to inorganic form. These cycles significantly influence atmospheric and oceanic chemistry and the global energy balance. The varied dynamical patterns reflected in different stages of these cycles are the consequences of a myriad of biological, chemical, and physical processes that operate across a wide spectrum of time scales.

For the IGBP, departures from biogeochemical “quasi-steady state” are of greatest interest. From ice core records, we know that atmospheric concentrations of carbon dioxide ( $\text{CO}_2$ ) and methane ( $\text{CH}_4$ ) were substantially reduced during periods of peak glaciation

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This paper is the result of discussion at a workshop (see the appendix to this paper) and further discussions among members of the Committee on Global Change.

relative to interglacial or recent "preindustrial values." What is fundamentally different in the very recent record since industrialization began is the rate of change:  $\text{CO}_2$  has increased at rates and to levels for which we have no historical or natural analogue back through the last two interglacial events. Moreover,  $\text{CH}_4$  is increasing in the atmosphere at a rate more than twice as fast as  $\text{CO}_2$  and is now at a concentration of almost 5 times that which was present during glaciation. These recent perturbations are believed to be anthropogenically induced. It is of great importance to develop an understanding of the factors responsible for the rapid rise in  $\text{CO}_2$  and  $\text{CH}_4$ , as well as the concurrent changes in the nitrogen, phosphorus, and sulfur cycles.

Understanding the biogeochemical cycles of carbon, nitrogen, sulfur, and phosphorus and the interactions of these cycles is of fundamental importance to the IGBP (National Research Council 1985, 1986). Although biogeochemical cycling in the terrestrial environment, rivers, the ocean, and the atmosphere is intricately interrelated, processes controlling the cycling are distinctly different in each of these environments. Thus, in order to identify scientific priorities for understanding biogeochemical cycles in the context of global change, in this paper each of these environments is discussed separately.

### BIOGEOCHEMICAL CYCLING IN TERRESTRIAL SYSTEMS

The accumulation and cycling of carbon, nitrogen, and sulfur within terrestrial ecosystems are ultimately controlled by the interaction of climate and the amount of phosphorus in the parent material. However, nitrogen supply is often the proximate factor regulating carbon fixation and storage, particularly in temperate, boreal, and agricultural areas. Patterns of carbon, nitrogen, and phosphorus turnover vary within and among biomes, responding to topography, land use, herbivory, and hydrology. For example, in cold-dominated, wet tundra ecosystems, carbon fixation exceeds decomposition; there is net carbon and nitrogen storage in soil, and plant growth is limited by nitrogen. In contrast, tropical forests on old infertile soils cycle large amounts of carbon and nitrogen, but biomass accumulation is limited by phosphorus.

At least three types of change are relevant to terrestrial biogeochemistry. First, changing climate will vary the balance between carbon fixation and release—partly because photosynthesis responds

less to changes in temperature than does respiration, and partly because water availability strongly influences storage and release of carbon. Second, changing the supply of carbon, nitrogen, phosphorus, or sulfur can alter the storage and release of all four elements. Finally, human changes in land use, associated, for example, with agriculture or pasture, can cause very rapid changes in carbon and nitrogen storage in terrestrial ecosystems.

In many cases, we know the direct effects of changes in climate, element supply, or land use on primary production: elevated temperatures increase growth of tundra plants, and elevated atmospheric  $\text{CO}_2$  concentrations increase carbon fixation in most plants. However, the ramifications of such changes at the ecosystem level are less clear.

For example, suppose elevated levels of  $\text{CO}_2$  increase carbon fixation in a forest with low nitrogen in its soil. The added carbon increases the C/N ratio in plant tissue. Such a change could affect herbivores either positively or negatively, depending on the chemical form of the additional carbon. Eventually, plants or plant parts return to the soil, where their elevated C/N ratio will affect rates of decomposition and nitrogen release, probably negatively. Consequently, ecosystem-level storage of carbon may be greater than expected from the simple increase in plant carbon fixation due to elevated atmospheric  $\text{CO}_2$  levels. The rate of plant litter decomposition would ultimately be decreased. Trace gas production would also be affected if changes in decomposition rates alter soil mineral-nutrient dynamics. However, if the decomposition and nutrient release in the soil are sufficiently delayed, nutrient limitation could become more severe, decreasing rates of carbon fixation and hence decreasing carbon storage.

In the context of changes in biogeochemistry in terrestrial systems, five geographic areas are judged as critical foci for experimental ecosystem studies; wet tundra, boreal forests, temperate forests in areas receiving nitrogen deposition, tropical forests, and semiarid ecosystems. These are selected for their potential sensitivity and contribution to global change.

### Tundra

Tundra is particularly important because of the large store of organic carbon contained in soils as a consequence of slow deposition caused by cold temperatures and waterlogging. Greenhouse warming



is predicted to be most pronounced at high latitudes, and may be expected to increase  $\text{CO}_2$  fixation by plants and to increase decomposition and  $\text{CO}_2$  release. However, if the climate also becomes wetter, the pool of organic soils in the tundra may increase, with the result that there may be an increase in carbon accumulation but with an associated increase in the release of  $\text{CH}_4$ . Experimental studies are needed to test these hypotheses.

The interactive effects of  $\text{CO}_2$  and climate can be addressed through controlled studies. Replicated greenhouses with elevated temperatures and/or  $\text{CO}_2$  have been established in tussock tundra, and growth and net  $\text{CO}_2$  fixation have been measured for three growing seasons. This established in part the basis for what is needed: a large-scale effort (large greenhouses, year-round sampling, studies on arctic coastal plain and subarctic mire as well as upland tundra, investigations of interactions with the nitrogen cycle) to (1) elucidate the net effects of climate- $\text{CO}_2$  interactions on carbon and nitrogen storage and (2) clarify their probable feedbacks to the greenhouse effect. The low physical stature of tundra ecosystems makes them particularly suitable for such an experimental approach, although their remoteness and the harshness of the environment pose a significant challenge. As a first step, low-stature temperate systems could be used as candidates for enclosure experiments under climate and  $\text{CO}_2$  and nutrient treatments.

In high latitudes, in situ and greenhouse experimental studies should be supplemented and extended through measurement programs to obtain net fluxes of  $\text{CO}_2$  and  $\text{CH}_4$  during warm versus cold periods over large spatial scales.

### Boreal Forests

Many characteristics of boreal forests, upon which prediction of responses to climate change could be based, are inadequately understood. Biomass densities, rates of nutrient cycling, and chemical characteristics of litter material would change as a consequence of greenhouse warming. An example of the potential importance of such change is that the temperature-moisture niche occupied by boreal forests no longer exists in many of the climate model projections for a doubled  $\text{CO}_2$ . Even granting the imperfection of climate models and the uncertainty of using temperature and moisture patterns as statistical estimators of potential vegetation, it is likely that major changes will occur in the high-latitude forests of the world.

How might the distributions and composition of boreal systems change? How might these changes feed back to the atmosphere and climate? What is the fate of the stored nutrients in these systems? Experiments to answer these and other questions need to focus upon the linkages between processes within boreal forests and climatic conditions. This is not done easily through enclosure experiments or even manipulations. However, natural gradients of climate within boreal systems could be used to gain much of the needed insights on their dynamics. Such gradients should cross both areas of high nitrogen deposition and unaffected regions.

### **Temperate Forests: Nitrogen Depositional Areas**

Nitrogen emission from industrial activity (and consequent redeposition) represents a large flux of nitrogen (ca.  $50 \times 10^{12}$  g/yr) and is globally significant relative to biological fixation. Moreover, the deposition is concentrated in temperate areas (eastern North America, northern Europe), where (at least in the past) nitrogen probably limits plant growth and carbon accumulation. Annual deposition in eastern North America (ca. 10 kg/ha/yr) is significant in comparison to annual nitrogen circulation in those forests (ca. 100 kg/ha/yr). In some areas of Europe, deposition is as high as 50 kg/ha/yr. How much of the nitrogen deposited is re-emitted as  $N_2$ ,  $N_2O$ , and  $NO_x$  or leached as  $NO_3^-$ ? How much additional carbon is fixed and stored as a consequence of deposition?

These questions can be approached in a manner analogous to that used to study effects of elevated  $CO_2$  in enclosure experiments. Controlled ecosystem-level studies can be set up in which treatments are applied including added nitrogen (low levels similar to deposition rather than fertilization), elevated  $CO_2$ , and changes in moisture and temperature regimes. The nitrogen portion of these measurements is under way at several sites. The interaction between elevated  $CO_2$ , altered temperature and moisture, and added nitrogen will require controlled glasshouse studies and could be supported by atmospheric boundary layer studies. Ecosystem-level modeling and measurement programs across natural gradients will be needed to supplement enclosure experiments.

Ecosystem-level enclosure experiments, as for the tundra, are essential since the added nitrogen may decrease tissue C/N and thereby increase decomposition/nitrogen release. While enclosure experimental work may be difficult because of the increased stature,

certain low-stature temperate systems do exist; furthermore, logistical difficulties, paramount in high latitudes, are less of a problem.

### Tropical Forest

The direct effects of increasing  $\text{CO}_2$ , possible changes in precipitation, and anthropogenic changes in tropical systems could all be globally significant. Tropical forests on young fertile soils are highly productive and circulate more nitrogen and phosphorus than any other terrestrial ecosystem. In contrast, infertile tropical soils (e.g., central Amazonia) remain relatively productive but are extraordinarily low in phosphorus. Conceivably, elevated  $\text{CO}_2$  could cause increased photosynthesis and possibly storage, but this may not be the case in the more infertile areas. It would be useful to undertake measurements to examine the question of whether increased  $\text{CO}_2$  increases photosynthesis in a range of tropical forests. It would be of particular interest to examine whether the increase in carbon fixation could cause increased nitrogen fixation, given the abundance of nodulated legumes in many tropical forests. This measurement is difficult because of the stature of tropical forests, but first steps could probably be addressed without chambers.

The distribution of precipitation in the tropics is interesting because of the very sharp transitions in both space and time between forest and savanna. Savanna is dominated by  $\text{C}_4$  grasses, stores less carbon and cycles less nitrogen than forest, and burns more readily (and often is present because of burning). The transition from forest to savanna and back thus could involve differential changes in storage of carbon and nitrogen and gas release (between or during fires). An understanding of the underlying mechanisms could indicate whether (1) areas currently forested can invade savanna areas (because elevated  $\text{CO}_2$  favors  $\text{C}_3$  species) or (2) human activity can convert additional forest to savanna. Such information would also be useful for interpreting the paleorecord during the last glacial cycle when, as many believe, much of what is now lowland forest was savanna.

Finally, current human population growth is concentrated in the tropics and will remain so for the foreseeable future. Large-scale land clearing is primarily a tropical phenomenon at present: the current range on the estimate of the rate of conversion of closed canopy tropical forest to agriculture is 70,000 to 100,000  $\text{km}^2/\text{yr}$ . Most natural systems dominated by perennials rapidly lose large amounts of carbon and nitrogen from soil upon conversion to agriculture:

the carbon as  $\text{CO}_2$  (except where wetland rice is established), the nitrogen as nitrate. Overall loss is often 25 to 40 percent of the amount in soil, and whereas this process takes 40 to 50 years in temperate regions, it can occur 10 times faster in the tropics.

Large fluxes of carbon and nitrogen are released with tropical land clearing. It is important to determine what systems are being converted, what the relevant standing stocks are, and what the rate of conversion is. Space-based observations are perhaps most appropriate for answering these questions. More difficult but equally important, we need to understand what regulates the rate and pathway of important loss of carbon and nitrogen following land clearing or conversion, and to establish what regulates the quantity and quality of carbon and nitrogen pools upon recovery. Such an effort would require determining the fraction of loss that occurs as  $\text{CO}_2$  versus  $\text{CH}_4$ , and as  $\text{NO}_3^-$  versus  $\text{N}_2$  versus  $\text{N}_2\text{O}$  versus  $\text{NO}_x$ . Nitrogen is particularly important because, while  $\text{NO}_3^-$  is the primary form of nitrogen loss in the temperate zone,  $\text{N}_2\text{O}$  and  $\text{NO}_x$  fluxes are much greater in tropical forests than they are in temperate forests. Most importantly, the mechanisms controlling pathways of loss or gain must be analyzed in order to extrapolate the fluxes over the range of land uses/ecosystems that are being affected.  $\text{CO}_2$  is also interesting; while elevated  $\text{CO}_2$  may not significantly affect forest carbon storage, it could certainly affect the rate of recovery on fertile sites.

### Semiarid Ecosystems

Humans depend very heavily on the livestock and agricultural productivity of subhumid and semiarid ecosystems, particularly in the tropics. Any changes in these areas, which are already marginal, would have important ramifications for human society. Subtropical areas may become drier with greenhouse-induced warming, which could interact with human-caused desertification (overgrazing, irrigation-induced salinization, accumulation of toxic metals) to cause large-scale changes in carbon and nitrogen storage and nitrogen gas production. Opposing this effect would be an increase in the efficiency of plant water use caused by elevated  $\text{CO}_2$ . Nutrient interactions will also occur since in most semiarid systems productivity is jointly controlled by water and nitrogen. Herbivory is ubiquitous in semiarid areas and greatly influences water, nitrogen, and  $\text{CO}_2$  dynamics, as well as other parameters controlling physical climatic interactions. Controlled studies involving both  $\text{CO}_2$  and aridity in

desert grassland, shrub-steppe, and dry tropical forest could determine whether the net effect would result in carbon storage or release.

In summary, there is a need for coordinated studies of selected ecosystems, to define the diverse impacts of human activity associated with altered supplies of carbon, nitrogen, and sulfur, and the sensitivity of paths for nutrient cycling to changes in climate. Integrative, coordinated studies of a broad areal extent over natural ecosystems are needed in an overall research strategy, as are experimental modifications, including enclosure experiments, of systems that can provide invaluable insights. Finally, a comprehensive strategy must include a commitment to a long-term observing system both from space and from the ground.

### BIOGEOCHEMICAL CYCLING IN FLUVIAL SYSTEMS

Rivers provide an important means for transfer of materials from the land to the ocean. They supply a significant fraction of the ocean's store of nitrogen nutrient and the bulk of its phosphate. Changes in this input may have particularly important effects on coastal ecosystems and in addition can affect oceanic productivity during the transition in and out of glacial periods. Rivers offer an excellent integration of biogeochemical processes operating in specific watersheds. Consequently, studies of riverine chemistry can provide an invaluable perspective on the significance of changes occurring over large regions. For these reasons, in consort with directed studies of specific terrestrial systems, they should play an important role in the overall strategy of the IGBP.

Estuaries and coastal regions are of particular interest. They may be expected to undergo especially rapid change due to the rising level of the ocean, which is anticipated to occur as a consequence of climatic warming over the next century or so. Sedimentary deposition in estuaries of major rivers can represent an important intermediate reservoir for phosphorus and nitrogen. As a result, processes that affect sedimentation and resuspension may exert a major influence on the flux of phosphorus and nitrogen to the ocean as well as having a direct influence on estuarial and coastal ecosystems. Recent studies suggest that inorganic processes in turbid estuaries may enhance the dissolved phosphorus-flux by up to a factor of 2. It is important to assess the size of the sedimentary reservoir as well as the factors that influence its deposition and erosion, and to identify how it might change in response to changes in climate.

Measurements of the chemistry of primary nutrients in selected major estuaries merit careful study. There is a need for a long-term measurement program to define the flux of phosphorus and nitrogen to the ocean, with attention directed to the role of sediments in estuaries and coastal regions in light of their potential importance as temporary holding reservoirs. Complementary laboratory experiments on sedimentary material will also be needed to clarify poorly understood chemical processes.

The residence time of dissolved phosphorus in the ocean is approximately 100,000 years. The time scale for changing the phosphorus-concentration in the ocean is therefore similar to that for major episodes of glaciation. The time scale for oceanic nitrogen is much shorter, about 10,000 years. Fluctuations in the terrestrial fluxes on nitrogen and phosphorus, due to variations in weathering and estuarine processes, and exchange with coastal sediments, could have an effect on temporal variations in oceanic nutrients, and consequently global climate, through changes in oceanic productivity. Thus previous models of the geochemical cycles of nitrogen and phosphorus that assume steady state behavior may need to be modified to explore implications of nonsteady state models for ocean nutrient cycles.

The supply of phosphorus to the world's oceans is controlled ultimately by the rate of continental weathering. Hence transport of phosphorus can be directly affected by climate through its influence on weathering rates. Studies of riverine chemistry can contribute to a better understanding of this interaction. Partitioning of phosphorus between aqueous solutions and solid phases depends upon the chemical conditions of the weathering environment. It is important to understand the mechanics of weathering under various climatic conditions in order to assess the chemical parameters that determine the initial partitioning between phases.

After weathering there is an opportunity for additional chemical alteration of solid phosphorus-bearing phases as phosphorus is incorporated in terrestrial ecosystems, and as it is transported in the rivers. It has been suggested that modifications of the chemical form of phosphorus can occur through surface interactions with colloidal metal oxides, and through dissolution caused by changes in solution parameters and biological activity. These matters merit further study.

## BIOGEOCHEMICAL CYCLING IN OCEAN SYSTEMS

### The Carbon System and the Biological Pump

The oceans are by far the largest active reservoir of carbon. Recent estimates of the total amount of dissolved inorganic carbon in the sea establish its range as between 34,000 and  $38,000 \times 10^{15}$  g carbon. Only a small fraction is  $\text{CO}_2$  (mole fraction 0.5 percent); the bicarbonate ion with a mole fraction of 90 percent and the carbonate ion with a mole fraction of just under 10 percent are the dominant forms of dissolved inorganic carbon. The dissolved organic carbon pool has been reported to be similar in size to the pool of terrestrial soil carbon, but recent data suggest that it may in fact be considerable larger.

Although the oceans are the largest active reservoirs of carbon and cover 70 percent of the globe, the total marine biomass is only about  $3 \times 10^{15}$  g C (though such estimates are uncertain at best), or just over 0.5 percent of the carbon stored in vegetation. On the other hand, the total primary production is 30 to  $40 \times 10^{15}$  g C/yr, corresponding to 25 to 40 percent of the total primary production of terrestrial ecosystems. A portion of this production results in a sink for atmospheric  $\text{CO}_2$ , primarily through the sinking of particulate carbon. As a consequence of this "biological pump," the concentration of dissolved inorganic carbon is not uniform with depth: the concentration in surface waters is 10 to 15 percent less than that in deeper waters. There is a corresponding depletion of phosphorus and nitrogen in surface waters, even in areas of intense upwelling, as a result of biological uptake and loss of detrital material.

The fate of this material depends, in part, upon its chemical characteristics. If it is in the form of organic tissue, then it is oxidized at intermediate depths, which results in an oxygen minimum and a carbon, nitrogen, and phosphorus maximum. If it is carbonate, it dissolves below the lysocline, raising both alkalinity and the concentration of carbon, at depths where the high pressure increases the solubility of calcium carbonate.

Thus the "biological pump" lowers the partial pressure of  $\text{CO}_2$  in surface waters and enhances the partial pressure in waters not in contact with the atmosphere. The efficiency of the biological pump depends on the supply of nutrients to surface waters, food web dynamics, and sinking losses of particulates to the deep sea. It may be expected to respond both to changes in the strength of the

overall thermohaline circulation and to variations in the abundance of nutrients, primarily nitrogen and phosphorus.

A portion of the nutrient flux to the surface returns to the deep sea unused by the biota, carried along by the return flow of waters in downwelling systems at high latitude. A high concentration of inorganic nutrients in downwelling systems would indicate that the efficiency of the biological pump is low and would favor transfer of  $\text{CO}_2$  from the deep sea to the atmosphere. It is important to define the physical, chemical, and biological processes that regulate the concentration of organic nutrients in descending water masses, the flux of so-called preformed nutrients. The concentration of preformed nutrients may be expected to reflect physical processes, and it can be influenced also by biological activity to the extent that this activity can result in packaging of carbon, nitrogen, and phosphate in fecal material that can fall to the deep, providing a path for transfer of nutrients from the surface to the deep independent of the physical processes such as those responsible for the formation of deep water in high latitudes.

There is a need for careful, coordinated studies of the processes responsible for transfer of nutrients from the surface to the deep. There is a particular need for studies of the relative role of physics and biology in regulating transfer at high-latitude, where the transfer mechanism may be influenced by seasonal variations in the extent of sea ice. Measurements must extend over all seasons, posing considerable difficulties in light of the logistical problems posed by the need for measurements during the harsh conditions characteristic of the high-latitude marine environment.

### Internal Nitrogen Cycling in the Ocean

In the ocean today the process of nitrogen fixation provides less than 1 percent of the nitrogen demand of the primary producers. Global contributions from riverine discharge plus wet and dry atmospheric deposition are thought to be similarly small. Nearly all of the nitrogen requirement is met by recycling via heterotrophic processes (ammonification and nitrification): ammonium, with lesser quantities of nitrate and nitrite, provides most of the nitrogen requirement for primary production in the sea. Organic nitrogen exists at intermediate concentrations, but the bulk of this material is very refractory, with turnover times of  $10^2$  to  $10^3$  years.

Some nitrogen is shunted out of this loop via permanent burial in



sediments, but the major loss of nitrogen from the marine system occurs because of denitrification, whereby nitrate is reduced to  $N_2$  and  $N_2O$  and lost to the atmosphere. This process is most active in the ocean today in the eastern tropical Pacific, in the waters underlying highly productive upwelling regions. In fact the best global estimates for denitrification lead one to conclude that, currently, nitrogen is being lost from the sea more rapidly than it is being gained.

Very little is known about the factors that regulate the dominant input term, nitrogen fixation. The most abundant oceanic cyanobacterium known to be capable of fixation, *Trichodesmium*, has never been cultured. At best, isolates have been maintained in the laboratory for a few months. When this organism is successfully established in laboratory culture, and optimal growth conditions defined, we will be able to ascertain better the factors that currently limit nitrogen fixation in the sea.

There is increasing evidence that eucaryotic phytoplankton, diatoms in particular, harbor intracellular inclusions of cyanobacteria that may be significant in terms of global marine fixation of nitrogen. Strategies involving monoclonal antibodies are now being suggested as a new approach to identifying and quantifying the process of nitrogen fixation in the sea. Undoubtedly, there are other opportunities yet to be explored that could bring the modern methods of molecular biology to bear on pressing issues related to the marine nitrogen cycle. It is essential that we develop a more complete understanding of the physical, chemical, and biological processes regulating the complex life cycle of nutrients in the sea.

### The Sedimentary Record

Certain geochemical and biological properties are recorded in oceanic sediments and form the basis for our deductions about global environmental changes. For example, we infer past temperatures of the ocean from counts of the relative abundance of the fossils of organisms preferring cold and warm ocean waters, or from measurements of the oxygen isotope composition of the fossils.

While the empirical and theoretical justification for these inferences is generally accepted, there is a distinct lack of direct global-scale documentation of the relationship between the sedimentation and geochemistry of fossils and the physical and chemical properties of the modern ocean. Such studies are imperative if we are to quantify the error limits to be placed on inferences concerning past

climates and ocean chemistry. They are essential if we are to recognize situations where our inferences may be misleading or in error. As an example, consider the carbon isotope composition of planktonic foraminifera from high-latitudes. One class of theories for the low glacial levels of atmospheric  $\text{CO}_2$  predicts that the  $\delta^{13}\text{C}$  in the high-latitude surface waters in glacial times should be shifted to reflect a larger abundance of  $^{13}\text{C}$  relative to the deep sea. In principle, we expect that we should be able to monitor past changes in high-latitude  $^{13}\text{C}$  using measurements of carbon in the shells of fossils that grew in surface waters. But it is reported that high-latitude planktonic fossils reveal a lower abundance of  $^{13}\text{C}$  in glacial times than would be indicated by theoretical expectations. Does this mean that the theories are wrong, or does it mean that the evidence is misleading? Perhaps it means that the foraminifera do not accurately record the  $^{13}\text{C}$  of the water they grow in, or perhaps that the sedimentary foraminifera were formed in a season other than that crucial to the theory.

Rather than reject either the theory or the oceanic evidence out of hand, a study of the global behavior of biological sedimentation, through ocean flux measurements, provides the opportunity to make a direct determination of the accuracy of foraminifera as recording systems for high-latitude surface  $^{13}\text{C}$  and the extent to which seasonal flux changes might bias the sedimentary record. With knowledge gained from studies of the contemporary ocean we would hope to be able to read the sedimentary record better and therefore derive valuable information on past ocean circulation, chemistry, and primary productivity.

Deep ocean circulation is one of the important controls on climate and atmospheric  $\text{CO}_2$ , due to its role in the global redistribution of heat, salt, and biochemically important elements. In order to predict future climate, it is important to understand the potential variability of deep ocean circulation. The study of past changes in ocean circulation inferred from deep-sea cores will provide a long-term perspective on the ongoing effort to develop an ocean climate model, in particular, with regard to past and future changes in atmospheric  $\text{CO}_2$ , as noted above. Ocean circulation modifies the effectiveness of the "biological pump" in isolating the atmosphere from the deep ocean and is a significant factor in controlling the alkalinity of the ocean through its influence on the deep ocean concentration of  $\text{CO}_3^{--}$  and the lysocline.

Data on geochemical tracers from fossils of bottom-dwelling organisms show that ocean circulation during the most recent glacial maximum was drastically different. In particular, it appears that North Atlantic deep water formation was significantly curtailed, while intermediate-depth waters in the North Atlantic were substantially more nutrient-depleted. Nonetheless,  $^{14}\text{C}$  studies of deep ocean fossils suggest that the overall ventilation rate of the deep ocean has remained similar to that of the modern ocean.

Continued development of a global database documenting three-dimensional changes in deep ocean circulation during the late Pleistocene is needed. Such a database should include measurements of carbon isotopes, cadmium, and  $^{14}\text{C}$  in benthic foraminifera. These measurements should be coupled with documentation of changes in the deep ocean carbonate system through studies of the preservation and accumulation of calcium carbonate in deep ocean sediments. The results of these studies should be coupled with biogeochemical models for the transfer of nutrients and carbon through the ocean. These goals can be achieved through the continued study of archive sediment cores, but will also require continued efforts to obtain suitable large-diameter cores in key parts of the ocean. Large-diameter cores are needed to provide material sufficient to allow simultaneous measurement of key properties as well as retention of archive material to be used as new techniques are developed over the next decade. Cores taken in regions of high sedimentation rates are needed to provide information on rates of change that have occurred in the recent past. Studies of the effects of rapid change, such as the Younger Dryas cold interval about 10,000 years ago, on ocean circulation and chemistry can provide valuable information on the response time of the global climate system.

A global carbon isotope data base will also be of use in the evaluation of the magnitude and rates of change of the continental biomass. Carbon that is currently in the biomass was transferred to inorganic form in the ocean during the last glacial maximum. The magnitude of the associated transfer should be reflected in the  $\delta^{13}\text{C}$  of benthic forams.

The magnitude and timing of past changes in the phosphorus content of the ocean will be key to obtaining an understanding of the global phosphorus cycle. Because of the long time constants involved (approximately  $10^5$  years), variability in sources and sinks of phosphorus are difficult to study directly on a global basis. But

the consequences of past imbalances between input and output of phosphorus in relation to climate change can be examined.

Most of the phosphorus in deep ocean sediments is detrital (i.e., it is what remains of the particulate phosphorus that fell through the water without being released to dissolved form), but it is difficult to make a satisfactory estimate of the rate of loss of dissolved ocean phosphorus into sediments. Because of the biological and climatological importance of the phosphorus budget of the ocean, it is important that continued attempts be made to overcome this difficulty. There are indications that much of the loss of phosphorus may occur in limited regions of the ocean (such as in areas of high biological productivity and/or low bottom water oxygen), and it is particularly important to encourage the study of authigenic phosphorus sedimentation in these environments. The success of these efforts will depend on significant breakthroughs in the methods of studying phosphorus sedimentation. The importance of the phosphorus mass balance justifies significant efforts in this direction.

Study of the past phosphorus content of the ocean is also a key in testing some models of past changes in atmospheric  $\text{CO}_2$ . The phosphorus content of the deep ocean is one of the most significant factors in setting the  $\text{CO}_2$  content of the atmosphere. Current evidence based on studies of the carbon and phosphorus analogues,  $^{13}\text{C}$  and cadmium, respectively, suggest that the oceanic phosphorus inventory has not changed as drastically in the past as suggested by some models seeking to account for the observed reduction of atmospheric  $\text{CO}_2$  (to 200 ppmv during glacial times). For example, the cadmium content of the ocean, which is empirically correlated with phosphorus concentration though the causal mechanisms are not clear, does not appear to have changed by more than 20 percent over the last 300,000 years. It is possible that the Cd/P content of the ocean is not fixed for long geological times. Further constraints can be placed by paired measurements of  $^{13}\text{C}$  and cadmium, since the slope of the relationship between these two properties depends on the oceanic phosphorus content. Progress can be made then without making any assumptions concerning the Cd/P ratio of the ocean.

In view of the importance of documenting changes in the phosphorus cycle of the ocean, extension of the database of paired  $^{13}\text{C}$  and cadmium measurements from benthic foraminifera from the late Pleistocene ocean, and exploration of the relationship between these properties in the more distant geological past, are imperative.

## BIOGEOCHEMICAL CYCLING IN THE ATMOSPHERE

An understanding of the factors regulating the chemistry of the atmosphere is essential to the success of the IGBP. The atmosphere provides an early warning of changes in globally dispersed ecosystems. Measurements of selected gases,  $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{N}_2\text{O}$ , hydrocarbons, and dimethylsulfide for example, can help diagnose changes in the metabolism of specific systems. In addition, we need a continuing focus on the significance and nature of the changes taking place in the troposphere and stratosphere.

The phenomenon of the antarctic ozone hole, its recent discovery and belated investigation, clearly attests to the still fragmentary nature of our understanding. We are just beginning to focus on the changes taking place in tropospheric  $\text{O}_3$ . There is growing evidence that the abundance of tropospheric  $\text{O}_3$  is increasing over large regions, that the urban smog phenomenon is no longer confined to cities. This has clear implications for productivity in impacted areas and may be expected to significantly affect biogeochemical cycling over extensive regions. The chemistry of tropospheric  $\text{O}_3$  assumes additional importance in that the abundance of OH may be expected to change in response to changes in lower atmospheric  $\text{O}_3$ .

The radical OH is the ultimate cleansing agent for a wide range of gases emitted to the atmosphere. It regulates oxidation of nitrogen and sulfur compounds and oxidation of CO, triggers the initial steps in oxidation of various hydrocarbons, and is responsible for removal of a wide variety of industrial halocarbons.

The abundance of stratospheric  $\text{O}_3$  is influenced by the input of halogenated gases. Oxides of nitrogen, introduced to the stratosphere by decomposition of  $\text{N}_2\text{O}$  and by processes triggered by absorption of cosmic rays and solar protons, play an important role in removal of  $\text{O}_3$ . The level of  $\text{O}_3$  is expected to change in response to changes in  $\text{CO}_2$ , leading to stratospheric cooling compensating tropospheric warming. An increase in  $\text{CH}_4$  can reduce the reservoir of chlorine radicals by favoring conversion of Cl to HCl. Changes in  $\text{CH}_4$  can also lead to changes in the abundance of stratospheric  $\text{H}_2\text{O}$ , with important consequences for the chemistry of  $\text{NO}_x$ ,  $\text{Cl}_x$ , and  $\text{O}_x$  and potentially for climate. It is essential that we develop an understanding of the factors resulting in changes in the abundance of all of the stratospherically relevant species, with particular attention to  $\text{CH}_4$ ,  $\text{CO}_2$ ,  $\text{N}_2\text{O}$ , and the halocarbons.

These objectives are being addressed in the stratospheric research programs coordinated mainly by NASA. They must continue

to receive vigorous attention. A significant role is played by  $\text{NO}_x$  in production of tropospheric  $\text{O}_3$ . In the presence of elevated levels of  $\text{NO}_x$ , oxidation of hydrocarbons, both natural and anthropogenic, is expected to lead to production of tropospheric  $\text{O}_3$ .

The phenomenon has been studied extensively in cities and is an important contributor to the formation of urban smog. There is evidence that effects of pollution on tropospheric  $\text{O}_3$  are widespread. Episodes of high  $\text{O}_3$  are observed over extensive spatial scales in summer in the eastern United States and in Europe. Levels of  $\text{O}_3$  are high enough to affect the productivity of agricultural crops and natural ecosystems. The interactions of evident changes in atmospheric chemistry and climate with vegetation must be better quantified.

Preliminary results from the Atmospheric Boundary Layer Experiment (ABLE) experiments in the Amazon Basin indicate that removal of  $\text{O}_3$  from the atmosphere is correlated with uptake of  $\text{CO}_2$  by vegetation. Experimental strategies have been developed to investigate this interaction. They should be applied to a variety of ecosystems if we are to understand how the biosphere responds to changes in atmospheric chemistry. We need to define the response of the biota to this change and how the chemical environment might be altered by the altered state of the vegetation.

Studies of experimentally manipulated systems would contribute to a better understanding of the underlying synergisms. These studies should include investigations of the consequence of deposition, both dry and wet, of acid species, particularly oxides of nitrogen and of sulfur. It is also important to study the response of natural ecosystems to enhanced levels of ultraviolet radiation, particularly so in light of recent evidence for a globally significant decline in the level of stratospheric  $\text{O}_3$ . Studies of tropospheric chemistry are less mature than studies of the stratosphere, but equally important.

The Global Tropospheric Chemistry Program and its national component (NRC, 1984; UCAR, 1986) are well formulated, but implementation is so far slow. There is a clear need for resources to be directed to these activities to stimulate the pace of research. The objectives are to understand the processes regulating the composition of the troposphere with particular attention to oxidants and to define paths for removal of biospherically formed gases.

The abundance of tropospheric  $\text{O}_3$  is expected to depend on rates of input of  $\text{NO}_x$  and hydrocarbons.  $\text{O}_3$  and other oxidants in surface air can interact with vegetation. We need to understand the factors regulating this interaction, its impact on the biota, and the nature

of the response of the biota as it might affect the emission of important chemical elements. We need a better understanding of processes regulating emission of  $\text{NO}$ ,  $\text{N}_2\text{O}$ ,  $\text{CH}_4$ ,  $\text{CO}_2$ , hydrocarbons, natural halocarbons, and hydrocarbons. This will require intensive investigations of specific ecosystems, supported by appropriate chemical investigations of the life cycles of these gases in the atmosphere. Our understanding of processes must evolve such as to allow prediction of the response of ecosystems to change. If our agenda is confined to simply describing what happens now, we shall fail seriously to meet our objectives. The current agenda for research in atmospheric chemistry is directed toward understanding the atmosphere as it is and as it may change in the immediate future. It recognizes the importance of the atmosphere as an agent for transfer of chemical species from one compartment of the biosphere to another ( $\text{NO}_x$  and  $\text{SO}_x$ , for example). It recognizes that emission of biogenic gases such as  $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{N}_2\text{O}$ , and dimethylsulfide can lead to effects on climate. It is important to extend this perspective to the past. The information contained in the paleorecord will allow models to be developed for the paleoatmosphere. These models in turn will play an essential role in the interpretation of the paleorecord. For example, it should be possible to estimate rates for production of  $\text{CH}_4$  in the past using measurements of  $\text{CH}_4$  in ice cores in combination with data on  $\text{NO}_x$  and other relevant species.

Fortunately, ice cores offer a record closely related to conditions in the atmosphere. Air bubbles preserved in ice provide a rare opportunity to determine the past composition of the atmosphere. We can see clearly recorded through time the changes in  $\text{CO}_2$  and  $\text{CH}_4$  since the beginning of the industrial revolution. Changes in atmospheric composition associated with major changes in climate are also preserved. The available data provide a glimpse of conditions in our atmosphere extending back to about 160,000 years before present (B.P.). It may be possible to expand this horizon even further, perhaps as far back as 400,000 years B.P., using the planned Greenland Ice Sheet Program II core from Greenland.

Our knowledge of the changes in atmospheric composition that have taken place since the industrial revolution is based almost exclusively on the measurements from ice cores. We know that the level of  $\text{CO}_2$  has risen from about 280 ppm to almost 350 ppm. The ice has provided also a record of  $\text{CH}_4$  that indicates that  $\text{CH}_4$  abundances have risen from about 0.7 ppm to a contemporary value near 1.7 ppm. Further, the ice core record has a limited overlap with

modern analytical measurements in the atmosphere, which provides an important test of the reliability of the data derived from the ice. Studies of the isotopic composition of  $\text{CO}_2$  in ice allow us to discriminate between sources of  $\text{CO}_2$  derived from biomass burning and  $\text{CO}_2$  from fossil fuel. When taking up  $\text{CO}_2$  during photosynthesis, vegetation discriminates against  $^{13}\text{C}$  and  $^{14}\text{C}$ . Consequently, vegetation, humus, and fossil fuels are depleted in  $^{13}\text{C}$ . Vegetation and humus are similarly depleted in  $^{14}\text{C}$ , but because  $^{14}\text{C}$  is not stable, there is no  $^{14}\text{C}$  in fossil fuels. As a consequence, when one oxidizes vegetation and humus versus fossil fuels, there are different dilution factors operating. Thus, given the period of fossil fuel combustion, a record of atmospheric isotopic ratios, the uptake of  $\text{CO}_2$  by oceans, and estimates of the fractionation during  $\text{CO}_2$  transfer from air to sea and from air to terrestrial vegetation, it is possible to provide solid checks on any model of the  $\text{CO}_2$  system.

Similarly,  $^{13}\text{CH}_4$  measurements are available and provide a stringent test of models seeking to account for the recent rise in  $\text{CH}_4$  as well as providing invaluable clues as to the nature of the processes responsible for the rise. There are indications that the preindustrial source of  $\text{CH}_4$  was isotopically lighter, by about 2 percent. An adequate model for  $\text{CH}_4$  must account for the isotopic composition of the preindustrial source and for the enhanced recent production of  $^{13}\text{CH}_4$ .

The ice cores also record anthropogenic disturbances in the cycles of nitrogen and sulfur. Industrial sources of  $\text{NO}_3^-$  and  $\text{SO}_4^{--}$  are seen clearly in cores from Greenland. These data are especially useful, in combination with general circulation models of the atmosphere, in assessing the long-term impact of human activities. Measurements of  $\text{NO}_3^-$  and  $\text{SO}_4^{--}$  in mid-latitude and tropical latitude glacial reservoirs can also be useful in this context.

The long-term record of change is equally illuminating. Studies of gases trapped in polar ice cores have shown that the level of atmospheric  $\text{CO}_2$  is low, about 200 ppm, in glacial times, rising to about 280 ppm during interglacials. It is generally assumed that variability in  $\text{CO}_2$  on such time scales must reflect changes in the function of the ocean, since the quantity of carbon stored in the ocean vastly exceeds that in the combined reservoirs represented by the atmosphere, soils, and terrestrial biospheres. However, evidence that  $\text{CH}_4$  appears to track climate is intriguing and puzzling. The concentration of  $\text{CH}_4$  reaches as low as 0.3 ppm at peak glacial conditions. Since terrestrial systems are thought to play a dominant role in production of



CH<sub>4</sub>—in contrast to the case of CO<sub>2</sub>, where exchange with the ocean is important—we expect that the new data on CH<sub>4</sub>, in combination with pollen records allowing reconstruction of the geographic distribution of biomes, will permit valuable information to be drawn concerning the past condition of the terrestrial biosphere.

Measurements of CH<sub>4</sub> in combination with data on H<sub>2</sub>O<sub>2</sub> and NO<sub>3</sub><sup>-</sup> should also provide clues to the changes that may have taken place in the chemistry of the atmosphere in the past. In turn, such studies will broaden the perspective of atmospheric chemistry, enhancing our ability to assess the present and hopefully predict the future. Measurements of atmospheric species interpreted in this manner can be used to monitor the metabolism of the global biosphere and can provide a focus for a wide range of paleo-investigations.

### SUMMARY OF RESEARCH OBJECTIVES

The detailed research needs to understand the biogeochemical component of global change as described above can be summarized in terms of the following general objectives:

- To develop a better understanding of the current disposition of the major biogeochemical elements. This requires better definition of the quantities of carbon, nitrogen, phosphorus, and sulfur stored in major ecosystems.
- To develop a long-term database documenting changes in environmental parameters that affect rates of nutrient cycling, including a record of changes in the geographical distribution of major ecosystems and their capacities as storage reservoirs for carbon, nitrogen, phosphorus, and sulfur.
- To enhance understanding of processes regulating disposition of nutrients in selected terrestrial ecosystems. This will require carefully crafted experimental strategies using a variety of approaches, including passive observations of natural systems, selected manipulation of natural systems, studies of large and small enclosures, and selected laboratory investigations. Experimental strategies should be designed to enhance understanding of how cycling of biogeochemical elements in specific terrestrial ecosystems might respond to changes in physical and chemical climate.
- To define the changes in fluvial chemistry that might occur as a consequence of changes in land use patterns. Riverine and lake studies can provide an integrated record of the large-scale impact of changes in watersheds. Such studies can also contribute to a

better understanding of processes regulating transfer of nutrients to estuaries, coastal ecosystems, and ultimately to the ocean.

- To improve understanding of the factors regulating fixation and denitrification in the ocean. Process studies to address this objective are needed.

- To improve understanding of controls on marine phosphate and to better define the influence of nutrient cycling in the ocean on the level of atmospheric  $\text{CO}_2$ . Processes at high latitudes merit special attention in this respect.

- To quantify sources and sinks of important greenhouse gases such as  $\text{CO}_2$ ,  $\text{CH}_4$ , and  $\text{N}_2\text{O}$  and to define the response of the biosphere to changes in atmospheric composition. Studies of atmospheric chemistry in combination with ecosystem investigations are needed, as are integrated studies of the troposphere and stratosphere.

- To use the archives of the paleoenvironment preserved in ice and sediments to help develop and test models of the cycling of major biogeochemical elements and the feedbacks and linkages.

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## APPENDIX: WORKING GROUP ON BIOGEOCHEMICAL DYNAMICS

February 20-21, 1988  
Harvard University  
Cambridge, Massachusetts

Michael B. McElroy, Harvard University, chairman  
Fakhri A. Bazzaz, Harvard University  
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# Ecological Systems and Dynamics

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Ecological systems play a complex role in global change, as previous documents have emphasized (Bolin et al., 1986; ICSU, 1986a,b; National Research Council, 1986a). The following questions illustrate the information required to improve understanding of the role of ecological systems in global change:

- What are the most significant global variables affecting the dynamics of ecological systems, and how can biotic responses to global change be predicted?
- What ecological processes and mechanisms require further understanding, and what data sets are essential to model biotic responses to global change?
- What are the temporal and spatial dynamics in the responses of ecological systems to global change? How can they be documented?
- How will transfers of materials across ecosystem boundaries be affected by global change?

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This paper is the result of discussions at two workshops on ecological systems and dynamics, one focusing on terrestrial systems and one on marine systems. The contributions of those participants listed in the appendix to this paper are gratefully acknowledged.

- How do past responses of ecological systems, recorded by the fossil record, aid in predicting future response to global change?
- What are the characteristics and generalities of the feedback processes between ecological systems and the global system?

The first five questions are discussed below. Feedbacks to the global system are referred to throughout this paper, and are addressed specifically in the companion paper on "Climatic and Hydrologic Systems." The final section discusses research priorities for the ecological component of a research program on global change.

Responses of ecological systems to global change are complex because of the inherent intricacies of ecological systems and their interactions with the physical system, and because those processes depend on the influences of history and scale. Furthermore, ecological systems encompass a vast array of temporal variability, with response times varying in different parts of a single, interacting system. In addition, multiple stresses inevitably affect virtually all biotic systems. As simple examples, Great Lakes fisheries are simultaneously influenced by the multiple impacts of eutrophication, toxic pollution, and the introduction and removal of species (Evans et al., 1988). Forest dieback occurs under changing conditions of acid precipitation, heavy metals, ozone, drought, complex forest demographics, and associated nutrient cycles (Klein and Perkins, 1987). The marine biotic community is also complex and highly variable, frequently demonstrating situations where the effects are removed in time and space from the events that caused them (Rothschild, 1986, 1988). These examples caution against efforts to predict biotic responses, for example, by simply correlating biological phenomena with the spatial distribution of climate or by using single-factor causation theories. Only limited success would be likely with these techniques because biotic responses are often nonlinear and involve feedbacks at many temporal and spatial scales (National Research Council, 1986b).

Because of these particular characteristics of ecological systems, studies undertaken in the IGBP must include experimental approaches that address multiple stresses at several levels of organization, including whole ecosystems. The following discussion describes the challenge of extrapolating local observations and experiments to larger scales, in order to connect the biotic and abiotic components and to understand feedbacks to the global system.

## WHAT VARIABLES DRIVE CHANGES IN BIOLOGICAL SYSTEMS?

### Changes in Climate

A doubling of the concentrations of radiative gases in the atmosphere is expected to lead to a rise in global temperatures of  $3^{\circ}\text{C} \pm 1.5^{\circ}\text{C}$  (Jaeger, 1988). Global temperatures will change rapidly, the rate of increase ranging between  $0.1^{\circ}\text{C}$  and  $0.8^{\circ}\text{C}$  per decade (see Figure 2 of the companion paper on "Climatic and Hydrologic Systems"). The spatial and temporal patterns of temperature increases will be heterogeneous and are expected to be greatest in the northern mid-continent region of North America and Eurasia (R.E. Dickinson, personal communication). Although general circulation models do not agree on the magnitude of change, all models predict a change in precipitation in the mid-continent. An important observation is that not only will the predicted temperatures be higher than any experienced during the last several million years but the rates of change are more than an order of magnitude faster than any recorded in Quaternary history (M. Davis, personal communication, University of Minnesota). Ecological systems would therefore be required to respond to quite different temperature conditions from those of the past millions of years, which raises questions about their potential adaptive response.

The enormous significance of the rate of temperature change can be appreciated when spatial displacement is considered. A temperature rise of  $5^{\circ}\text{C}$ , for example, would imply northward displacement of isotherms in North America by 500 km. This change could occur within 100 years (Jaeger, 1988). Range extensions or movement of forest trees during the Holocene, recorded by fossil pollen, was only 25 to 40 km per century (Davis, 1981; Huntley and Birks, 1983), with the fastest range adjustment by spruce into northwestern Canada at 200 km per century (Ritchie and MacDonald, 1986). Given these rates of plant dispersal, vegetation would not be able to change its geographical distribution as fast as the changes in suitable habitat. As a result, there would be lags decades in length in the adjustment of ecological systems to rapidly changing climatic conditions. These lags in the match between climate and vegetation will become apparent in the mid-continent long before doubling of carbon dioxide has occurred. This phenomenon is described in Figure 1, which shows an example of how the geographical distribution of suitable climate

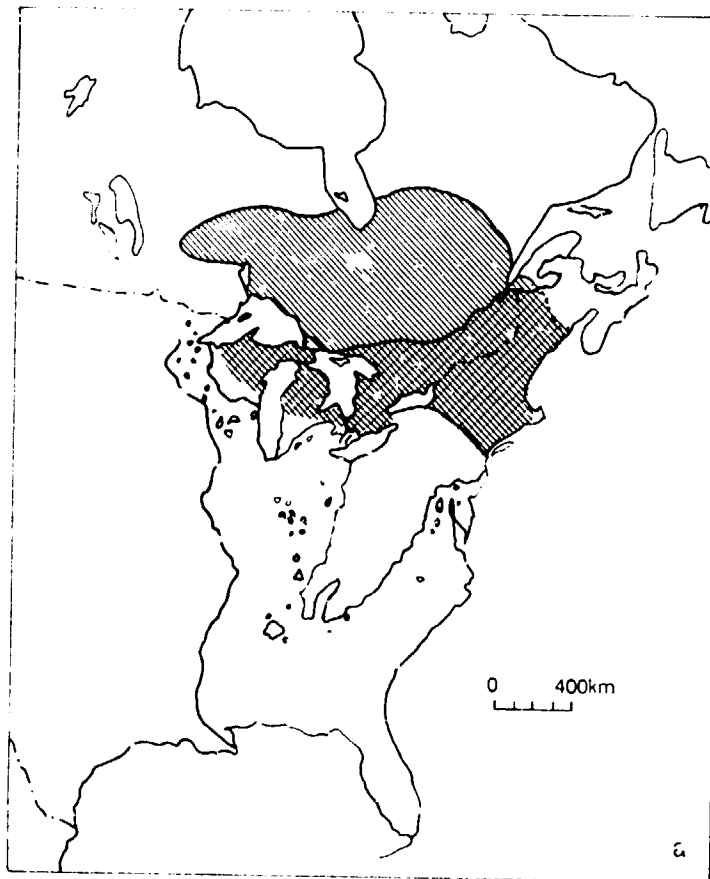
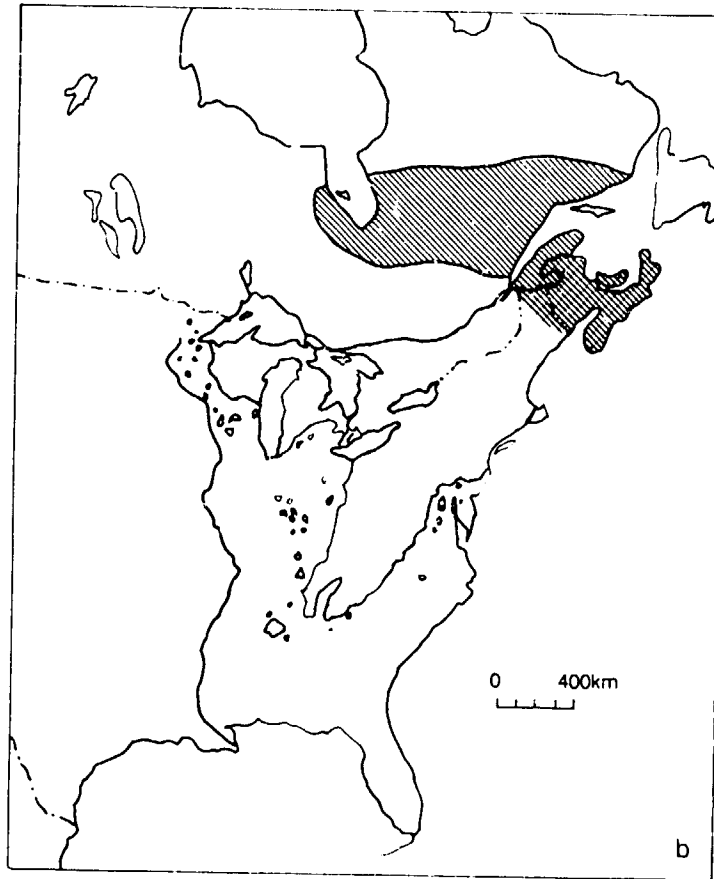


FIGURE 1 Present and future range for a common forest tree, eastern hemlock (*Tsuga canadensis*), under climate scenarios predicted by (a) Hansen et al. (1983) and (b) Manabe and Wetherald (1987). Horizontal shading is the present range, and vertical shading the potential range with CO<sub>2</sub> doubling. Cross-hatched area of

and the actual geographical distribution of a tree species may fail to coincide 100 years from now (Zabinski and Davis, unpublished data).

Ecophysiological responses to stress and the ability of plants and animals to reproduce and establish themselves ultimately determine the geographical range limits of individual species. Frequently, for example, in Figure 1, critical threshold values are now deduced from climatic correlations with geographical distributions, but more quantitative experimental data on responses are needed, as well as additional empirical observations, e.g., from dendrochronology (Garfinkel



overlap is where the trees are likely to be found 100 years from now. Relict colonies might persist to the south in pockets of favorable environment. Significant advance to the north is unlikely, as rates in the past were about 25 km/100 yr, and the most rapid rate known from the fossil record (for spruce) is only 200 km/100 yr. As a consequence, much of the potential range will remain unoccupied.

and Brubaker, 1980). Direct physiological observations are needed for plants and animals near their range limits.

In addition to the ecophysiological processes of the organisms, reproduction dynamics will affect rates of in situ population change and the rate of population diffusion to new geographic locations (Brubaker, 1986). Migration and the ability to colonize new habitats will affect the ability of species populations to track climatic change.



Existing data on exotic species may prove particularly useful in predicting species' responses to environmental change. For example, the population dynamics of successful invaders (Harper, 1977) may provide information needed to predict which species will spread and expand in response to changed future environments. Such an analysis would define the genetic characteristics of a species that allow it to expand or that contribute to its extinction in response to environmental change. It would also provide data to indicate how the genetic structure of future populations would be affected. Responses to past catastrophes, such as major extinctions of organisms, and documentation of which species survived and which became extinct, will be valuable to these studies. Also, evaluation of the habitats susceptible to biological invasions will permit a complementary approach for identifying likely spatial responses of biotic components to changing global climate.

Quaternary paleorecords document rates of range expansion and also show that species do not necessarily move as a group but have responded to change individually (Davis, 1981). As a result, ecosystems that are of limited spatial extent today may have been much more expansive in the past. An example is the oak savanna, which today forms the narrow ecotone between prairie and forest in North America, but which covered an area hundreds of kilometers wide during the mid-Holocene (McAndrews, 1967). Species that are rare or geographically localized today, such as bristlecone pine (*Pinus aristata*), were abundant in the past, while ponderosa pine (*P. ponderosa*), the dominant tree over large regions of the Rocky Mountains today, was very rare during the last glacial period (Spaulding et al., 1983). Spruce (*Picea*), which now characterizes the vast boreal biome, was sparse throughout North America in the early Holocene (Webb, in press). These examples show that one cannot assume that existing biomes will remain intact under future changes of global climate. The fossil record shows clearly that communities may be disassembled and species reassembled in new combinations in response to new climatic conditions (Davis, 1981; Graham, 1986). The resulting new combinations of vegetation, climate, and soils can result in altered spatial patterns of such fundamental processes as net primary production (Pastor and Post, 1988). More subtle, but still important, processes such as evolved host-pathogen relationships may also be disrupted by the stress of new conditions, resulting in increased frequency of epidemics (Leonard and Fry, 1986).

Global change will have a major impact on biological diversity.

Although absolute, and even relative, rates of species extinction and formation are not known precisely, changes in species and species number have presumably been a continuing process. There are now, however, conditions that have not been present over the past thousands of years. Human activity now adds substantially to changes in habitat on a global basis and, as a consequence, increases the loss of species (Lovejoy, 1980). This factor will be exacerbated by future climatic changes, which will alter the scale and patchiness of landscape units (e.g., forested versus unforested areas), both through direct effects and indirectly by changing patterns of land use by the human population. To analyze the combined impact of these changes, information is needed on (1) how landscape pattern affects species survival and extinction, (2) the effect of patchiness on dispersal to new habitats, (3) the effect of species interactions on survival and extinction, and (4) direct effects of human activities on abundance and distribution of organisms. Certainly, fragmentation will result in fewer pathways for species migration toward favorable habitats. In this regard, small ecological reserves may be especially vulnerable to the effects of climate change (Peters and Darling, 1985). A likely result will be the extinction of species that such reserves were established to preserve.

A fundamental question in the context of global change is whether changes in species composition and diversity will significantly affect ecosystem function. There are examples where ecosystem function appears to be relatively independent of species composition (Schindler, 1988). There are also examples where changes in species have had remarkable alterations in ecosystem processes, for example, the alterations produced by key predators such as the starfish *Pisaster* in the rocky intertidal (Paine, 1966) or the wolf on Isle Royale (Mech, 1966). A single nitrogen-fixing species can have a large effect on succession (Crocker and Major, 1955; Vitousek et al., 1987). Thus, quite aside from the question of biodiversity per se, the question of species replacement in ecosystem function must be addressed in a much wider array of ecosystem types.

Biological and atmospheric properties are coupled through several fundamental cycles, particularly the carbon and hydrological cycles. Predicting feedbacks to the climate system involves predicting how communities and key species in those communities will respond to changed climate. A major question is whether responses can be generalized from existing ecosystems. Because climate change will be large, species turnover will often occur, changing ecosystem

properties in many (although not all) cases. Thus the influence of species composition on ecosystem properties becomes a critical issue.

Climate change will also have direct effects on ecosystem processes and gas exchange with the atmosphere. General principles linking environmental factors (temperature, light, nutrients) to whole plant carbon fixation and allocation above and below ground and to photosynthetic versus nonphotosynthetic tissue are just now emerging (Bazzaz et al., 1987). Effects of climate variables on plants and soils can be determined using field and laboratory approaches. However, complex interactions of soils, plants, and climate occur. Recent simulation of climate change in semiarid grasslands revealed a strong, transient (ca. 50 to 100 years) increase in net primary production, despite drier conditions in the model (D. Schimel, personal communication). This was because higher temperatures led to higher rates of microbial mineralization of soil nutrients. The increase in nutrient availability in the simulations compensated for the reduction in moisture until soil reserves of nutrients were depleted, at which time production crashed. The intensity and timing of the transient varied regionally, depending upon levels of primary production and initial soil organic matter. Similar interactions are simulated for forests (Pastor and Post, 1988). For global applications, results from such studies must be generalized from the systems in which detailed studies are available. This research indicates that measurements of variables that control ecosystem response to change must be made over large areas for input to global models.

For aggregation of biological data from regional to global scales, remote sensing of vegetation structure and composition, land form characteristics, and certain biophysical characteristics will be necessary. Because of the potential for repeated coverage of the globe, satellite observations should provide useful data at many scales. Remote sensing provides information on states of specific variables, but it does not yet provide actual measurements of a process or flux. For these measurements, new technology is becoming available. Airborne and ground-based laser-based systems, such as LIDAR (light detection and ranging) technology, tunable diode lasers, and Fourier-transformed infrared spectrometry, allow measurement of atmospheric gas concentrations at varying scales (Harriss et al., 1988; Matson and Harriss, in press). Changes in gas concentrations can be coupled with aerodynamic physical flux measurements to estimate exchange of gases (such as  $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{N}_2\text{O}$ , and  $\text{NO}$ ) between terrestrial ecosystems and the atmosphere. These approaches are just

beginning to be applied generally to ecological questions, but initial tests have proven very encouraging (Gosz et al., 1988).

In the marine environment, the record of the past leaves little doubt that global warming will result in different distributions of planktonic organisms than those of today (CLIMAP Project, 1976). If in the simplest case the ocean warming were to be positively correlated with latitude, one would expect that the expansion of habitat in a poleward direction, which has occurred during the Holocene, would continue. But when one recognizes that the mean global warming projected for the next several decades is comparable to that experienced in the last 20,000 years, questions immediately arise regarding the potential of the biota to accommodate to these rates of change. Also, our knowledge of plankton distributions in the past is based on data for the few taxa, such as the foraminifera, that have easily preserved hard parts. Because the ecological role of these protozoans is not well known, it is difficult to predict the degree to which changes in their species composition indicates a change in the plankton community in general.

Increased warming and precipitation will decrease the density of surface waters, especially at high latitudes. If the warming and freshening of the surface water outpace the processes of convection and isopycnal mixing, vertical diffusion between the surface and the main thermocline could be much slower. This isolation of the main thermocline could severely impede the vertical transport of remineralized nutrients, severely diminishing the huge spring bloom characteristic of the North Atlantic. At high arctic latitudes, the reverse could occur. At present, very strong stratification is maintained because the freezing, high-salinity waters produced on the continental shelves during pack ice formation are incorporated into the thermocline. Thus the warm inflowing "Atlantic water" cannot upwell and is completely isolated from the surface layer. Warming and freshening will diminish ice formation and could lead to an ice-free Arctic. Ventilation of the main thermocline of the Atlantic from the Arctic via the Greenland-Scotland overflows could occur, with the result of much higher rates of primary production and nutrient cycling.

The regional effects of global warming on the plankton habitat in near-surface waters are unpredictable at present. Strength of wind fields and their orientation will vary. Along-shore winds contribute to the upwelling process in many coastal waters and across the equatorial Pacific. The direction, intensity, duration, and frequency of these wind events determine the extent and timing of upwelling

events. Because this process, which is typically highly seasonal, is very important in stimulating the primary production processes that lie at the base of the food webs for many commercially exploited species, it can be anticipated that global climate change will have significant economic consequences, especially for the fish-harvesting nations.

Changes in the intensity and frequency of stratification and destratification processes will have differential effects on plankton, depending on their physiology and anatomy. Diatoms, for example, are phytoplankton that typically dominate in cold nutrient-rich waters, such as those that have recently upwelled. Because of their high sinking rates, diatoms are also major contributors to the flux of carbon to the deep ocean (Smayda, 1970). A turbulent mixed layer also seems to be a requirement for diatom success. Diatoms are the preferred food of many organisms in the food webs of commercially exploited fishes, and when replaced by other types of phytoplankton—the dinoflagellates, for example, in the case of the Peru Current—the yield of the fish of greatest economic interest is reduced dramatically (Barber and Chavez, 1983).

There is some evidence that at least some economically important seaweeds may be quite sensitive to increases in water temperature. During the 1982-1983 El Niño event in Chile, the northern populations of the alga *Durvillea* disappeared and have not yet recolonized (Tomicic, 1985). The kelp, *Laminaria japonica*, is grown extensively in the warm waters of China because one phase in the life cycle that is particularly temperature sensitive can be cultured, after which young sporophytes are outplanted on rafts, where they grow to harvestable size (Tseng, 1981). Because the sporophytes are probably near the limit of the temperatures in which they can survive, an increase in water temperature of only a few degrees could eliminate the entire industry.

Populations of valuable fish and shellfish undergo fluctuations in abundance of order of magnitude on time scales ranging from one to a hundred years. Examples include the collapse of the Peruvian anchoveta and the California sardine population (Murphy, 1977), the decline and then increase of the Japanese sardine (Kondo, 1980), substantial declines of shellfish such as the oyster of Chesapeake Bay (Kennedy and Breisch, 1983), and changes in distribution, such as contraction of Atlantic salmon distribution along the coast of North America in the present century (B. Rothschild, personal communication) or the areal expansion of triggerfish to much of the coast of

Africa during the past decade (Gulland and Garcia, 1984). It appears that a number of these population changes result from changes in the distribution of temperature. A more fundamental understanding of ecological processes is needed to understand the consequences of climate change, particularly the interactions with the dynamics of associated populations, and especially plankton.

### Changes in Human Land Use

For the last century, and presumably for the next, land use has been more important than climate change in forcing changes in ecological systems and dynamics. In addition to examples such as the effect of deforestation on biodiversity in the tropics, land use changes affect a large number of ecological and physical ecosystem properties that control interactions with the atmosphere and hydrosphere. Land use affects storage of carbon, nitrogen, and phosphorus in the soil, as well as element storage in the biota. For example, slash-and-burn agriculture releases nutrients from the biomass to the soil, with concomitant releases of gases to the atmosphere (Mooney et al., 1987). Mechanical disturbance of soil, by plowing, results in organic matter loss and alterations in soil structure and porosity, which in turn alter moisture regimes, microbial processes, and emissions of trace gases to the atmosphere. Removal of vegetative cover, as well, decreases net primary production and net ecosystem production, and fluxes of water to the atmosphere through evapotranspiration. Deforestation dramatically increases sediment and dust production, runoff, and solute concentrations, with consequences for biota in lakes, estuaries, and coastal zones (Bormann and Likens, 1979). Finally, land conversion affects the diversity of ecosystem types both globally and regionally and, in particular, causes loss of species (Lovejoy, 1980). What aspects of land use need to be characterized in order to address potential changes in ecological systems? The primary need is for data in categories of cover types: natural vegetation (specified in terms of biomass and stature), arable land, grazing land, permanently flooded land, nonproductive land. Within the arable land category, data are needed on three additional factors to characterize land use: water use, fertilizer use, and biocide applications. For each expressed need for land use data, it is necessary to specify the scales and resolution (time and space) and the level of accuracy needed for data to describe land use adequately to assess its relation to the changing global environment.

Three additional types of land use information are needed. First, reconstructions of past land use change are needed for use in conjunction with reconstructions of ecological systems. The overriding need with respect to global change is for data on a regional scale, extending back to about 1850 to cover the period of intensive human transformation of the earth's surface. Longer reconstructions on a regional and even on a continental scale are possible using the pollen record (Darby, 1956). The timing of large-scale changes, such as the deforestation of Europe and the development of agriculture in China and other regions, should be compared with ice core records of changes in atmospheric composition. Second, land use data will need to become a routine component of contemporary monitoring efforts. Remote sensing can be utilized to provide a record of rates of change, especially in the tropics, where deforestation is proceeding rapidly. Third, future scenarios of land use change are needed to predict changes in biotic systems and interactions within the global system. This predictive process will require the combined initiative of biologists, demographers, development economists, and agricultural experts.

### Changes in Carbon Dioxide

The primary effects of increased carbon dioxide concentration are increased photosynthetic rates and decreased stomatal conductance, which reduces water loss and causes changes in plant phenology (Carlson and Bazzaz, 1980). Most studies with agricultural crops and species from natural communities indicate that productivity and yield increase with elevated  $\text{CO}_2$  levels (Strain and Cure, 1985). Plants with the  $\text{C}_3$  metabolic pathway generally show more enhancement of photosynthesis and growth in response to elevated  $\text{CO}_2$  than plants with the  $\text{C}_4$  pathway. This response has a clearly understood physiological basis. There are also differences in response to elevated  $\text{CO}_2$  among species and among genotypes within species, but the bases for these differences have not been fully investigated (Bazzaz et al., 1985). Studies of whole communities, however, do not always show enhanced productivity. A community of short-statured annuals showed no response (Williams et al., 1988), and short-term measurements of some deciduous tree species showed only a small enhancement in growth (Williams et al., 1986). The response to elevated  $\text{CO}_2$  productivity of natural vegetation is therefore still

somewhat unpredictable, but nevertheless essential for understanding the relationships between primary production and changes in the global environment.

High CO<sub>2</sub> concentrations may change the pattern of carbon allocation to plant parts and activities, but the available data are inadequate for describing general patterns (Bazzaz et al., 1985). There may also be shifts in the kinds of chemical defenses in plant tissues and changes in rates of plant tissue consumption by herbivores (Lincoln et al., 1984). Decomposition rates and nutrient cycling may change in response to altered plant C/N and lignin/N ratios, as well as changes in starch content, leading to feedback via decomposition restricting the positive effects of CO<sub>2</sub> enhancement (Melillo et al., 1982).

Experimental studies in which whole plant communities have been subjected to elevated CO<sub>2</sub> show that competitive hierarchies change. The resulting community structure is influenced by other environmental factors such as moisture, light, nutrients, and temperature (Bazzaz et al., 1985). It is important to note that the response at the community level may not be directly predictable from the response of individual species to elevated CO<sub>2</sub> or to other environmental factors because of changes in species composition and interactions with heterotrophic organisms. Our knowledge of past responses of natural systems to changed CO<sub>2</sub> concentrations is also limited; the fossil record should be inspected for changes at the end of the last glacial period that can be related to changing CO<sub>2</sub> concentration in the atmosphere.

The response to enhanced CO<sub>2</sub> concentrations at the level of ecosystems has been the subject of only a few experiments (Drake and Read, 1981; Oechel and Strain, 1985; Tissue and Oechel, 1987) and is largely unknown. Of concern, particularly with respect to the global carbon cycle, are the rates of CO<sub>2</sub> storage and release of various ecosystems as affected by increased CO<sub>2</sub> concentrations (Billings, 1987), and the relationship of these variables to nutrient circulation. Feedback to the hydrologic cycle may be influenced by changed water use efficiency.

#### **Other Changes in Atmospheric Chemistry and Pollution**

Other changes in atmospheric chemistry have potentially large, landscape-level effects on ecological systems, primarily through effects on ecosystem components, especially those with slow turnover



rates such as soil organic matter and long-lived organisms such as trees and fish. The regional scale of pollution and the transport of pollutants across political boundaries make these issues of global concern. Synergistic effects of various pollutants are well known from simple laboratory experiments (Mansfield et al., 1987), and these effects will certainly be found in the study of ecosystems. Ecosystem changes attributed to acid deposition alone, for example, may be the result of interacting factors. Forest decline may result from acid deposition, associated pollutants, ozone, disease/pest outbreaks, changing forestry practices, and/or interactions among any or all of these factors (Hutchinson and Meema, 1987). In lakes, changes inducible by acid rain (Harvey, 1982) are also inducible by certain metal pollutants (National Research Council, 1972) and fishery management practices. Experiments are needed to determine physiological tolerances to multiple stresses. Tolerances to different stress factors are not linked and therefore are inherited independently; hence it seems unlikely that organisms will spontaneously evolve tolerances to multiple simultaneous or sequential stresses. Furthermore, purposeful breeding for stress-tolerant organisms will also be difficult.

Knowledge of which pollutants will increase in the future, and by how much, is needed to define the areas requiring attention in the IGBP. This information will be derived from expected rates of industrial and technological development. It is clear, however, that a focus on suites of associated pollutants and multifactorial responses at individual, population, and ecosystem levels is needed to unravel complex causes of damage to ecosystems. Because such experiments cannot be performed for each potentially important factor or interaction, the proper approach will be to carefully integrate laboratory and field experiments with simulation models, and with small-scale studies aimed at particular organisms or interactions. Innovative indices of responses to pollutants are needed for both survey work and retrospective studies. These results will be best derived from whole-ecosystem experiments. The effects of pollutants on heterotrophs, pathogens, or symbionts such as nitrogen-fixing bacteria must be examined in addition to the effects on plants.

The effect of pollutants on marine ecosystems is difficult to study, because suitable control sites are hard to identify, making the separation of even major pollutant effects from "natural" variability problematic. Another problem is that impacts can occur via indirect pathways. For example, an oil spill in the Baltic Sea caused a significant decrease in hatching of herring eggs. However, the result was not

because of a direct toxic effect on the eggs themselves; rather, the oil decreased populations of gammarid amphipods, causing decreased amphipod grazing on fungi and consequently increased fungal infection of eggs (Nellbring et al., 1980). Controlled ecosystem-scale experiments allow a holistic assessment of the responses of ecosystems to known exposure to pollutants, and are necessary to detect these indirect pathways.

### Changes in Ultraviolet Radiation

Changes in atmospheric constituents, especially stratospheric ozone, will affect the intensity of ultraviolet radiation reaching the terrestrial and marine portion of the biosphere. Previous investigations in arctic/alpine regions indicate that changes in ultraviolet irradiance will cause changes both in productivity and in distributions of specific vegetation types. More subtle effects on ecosystem processes like decomposition are less completely understood and yet have great importance in biosphere-atmosphere interactions.

The IGBP needs, first, to test the responses of characteristic vegetation types to a range of potential ultraviolet levels, focusing specifically on more subtle responses such as rates of decomposition of organic matter, susceptibility to plant diseases, species interactions, and genetic change. Intensified ultraviolet radiation will increase mutation rates, but it is not clear what effect this will have on population structure and viability. Theory is yet to be developed that will generate testable hypotheses regarding the effects of fluctuating mutation rates on susceptible species. Second, the IGBP needs to conduct experiments and develop models to predict the productivity and distribution changes of terrestrial and marine biota in response to increased ultraviolet radiation. Methodologies for extrapolation from experiments and measured sites to global scales require more development.

### Sea Level Change

The effects of the expected rate of sea level rise in the next century, nearly 1 cm/yr, may be somewhat analogous to the effects of sea level rise that occurred at the end of the last ice age, 80 m over an interval of 14,000 years (Bloom, 1988). Although it is clear that major dislocations in estuarine, marsh, and nearshore ecosystems occurred during deglaciation, our knowledge of ecological response is

inadequate to allow firm predictions. Available information suggests, however, that the predicted rates of sea level rise are near the upper bound of possible rates of intertidal marsh growth (Boamann et al., 1984). Consequently, sea level rise in the next century is likely to drown many if not all salt marsh systems except in areas where the land is rising and reducing the rate of relative sea level change.

Tidal marshes are important habitats because they are highly productive. They buffer nutrient availability in neighboring estuaries and provide critical habitat for migrating birds. Drowning of salt marshes will change the hydrology of estuarine systems. Rearrangement of channels can erode previously deposited sediments, exposing buried pollutants such as dioxin and mercury. A rise of water level in estuaries will have repercussions on fish habitat far upstream, which may be difficult to predict, because the distance a saltwater wedge will move upstream depends not only on sea level, but also on discharge rates in the river, which will be affected by climate. Increased precipitation could change discharge and result in increased erosion and sediment transport. Coupled with rising sea level, the result would be an increase in siltation of river channels leading to greater flood potential, and higher turbidity in estuarine zones, especially when higher sea level causes rapid coastal erosion.

Higher precipitation would also cause a rise in the water table and its propagation shoreward. This will be countered by the sea level increase. Thus it seems likely that the fresh and salt transition zone will move, although the direction is not predictable. Because this front is of great ecological significance, it will be necessary to examine the probable magnitude of the effect using numerical models of coastal zone aquifers.

A question of vital interest, especially for low-lying islands, is whether coral reefs can grow at rates comparable to the projected sea level rise, particularly when the effect is combined with increased water temperature (Mathews, 1984).

Rocky shores in temperate latitudes support very productive intertidal and subtidal communities, which in turn support the detrital-based food webs of nearshore fish and shellfish communities, as well as adjacent sandy beach fisheries. In some countries, seaweeds and invertebrates are also used directly and extensively by humans (Santelices et al., 1984; Tseng, 1981, 1984).

In the intertidal, as in many other ecological situations, the variance of the physical parameters, especially air temperature, is more

important than the mean. Quite often it is the catastrophic event—the coincidence of daytime low tides with unusually hot weather, for example—that determines the distribution patterns of longer-lived sessile organisms (Glynn, 1968; Hughes et al., 1987; Lessios et al., 1984; Loya, 1976a; Wethey, 1985). Therefore the IGBP research program must include an experimental design that recognizes and accommodates these episodic events.

### **WHAT PROCESSES REQUIRE FURTHER UNDERSTANDING IN ORDER TO MODEL BIOTIC RESPONSES TO GLOBAL CHANGE?**

A long-term goal for the IGBP is to develop interactive models coupling the exchange of matter, such as  $\text{CO}_2$ , water, and trace gases, as well as exchange of energy and momentum, between ecosystems and the atmosphere. Currently, ecosystem and atmospheric models are for the most part separate, with ecosystem models using externally specified climatic drivers, and climate models treating ecosystems as static boundary conditions.

Modeling ecosystem response can take one of two forms, a process-functional approach or a population-community approach. Process-functional models simulate fixation, allocation, and decomposition of carbon, cycles of nitrogen, phosphorus, sulfur, and other elements that exchange across system boundaries. Population-community models represent birth, growth, death, and movement of organisms or groups of organisms, and can simulate changes in abundances of species within and between ecosystems (e.g., Botkin et al., 1972). The selection of one of these approaches over the other depends on the question being asked. Many research teams have chosen the process-functional approach because of the importance of biogeochemical cycles in short-term (1 to 100 years) ecosystem response to global environmental change. This is in part because rates of element cycling may change more rapidly than species composition (days to years versus years to centuries). However, as populations and communities change, so do controls over biogeochemical cycling such as plant tissue element ratios and detrital organic chemistry (Pastor and Post, 1986). In a reciprocal fashion, a change in nutrients and other resources is a driver of population and community processes. Thus general models linking biogeochemical cycles to population and community processes will be required to model ecosystem consequences

of global change (Pastor and Post, 1988). Several models have successfully blended the two approaches by tracking changes in those properties of individual organisms or cohorts that are important at the ecosystem level, such as carbon or nitrogen content and decay rates of annual cohorts of litter (Figure 2).

Paleoecological data provide a key to unraveling the rates of transition between vegetation types resulting from climatic change (Jacobson et al., 1987). Current models must address the issue of how much climate-induced process-level change (photosynthesis, decomposition, nutrient cycling) occurs within ecosystems before community turnover and biome-type change occur, and, conversely, to what extent species changes drive process-level changes in these systems. Records from the past may elucidate the time frame and the driving functions for these changes (e.g., Chen, 1986; Grimm, 1984).

The paleorecord provides data sets, especially isotopic records, that should be used more extensively in global change research to test process-functional model predictions. The testing of long-term ecological/process models is a challenging area that involves inferential tests from a wide and rich mixture of paleoecological, historical, and experimental data.

Questions of scale must be resolved to link ecosystem models to models of atmospheric change. Physiological models simulate variations in carbon dioxide exchange or transpiration on time scales of minutes to months, but typically have low resolution of spatial differences. Atmospheric models require scales of minutes to days, but with much broader spatial representation. Models linking ecosystem and atmospheric change must simulate spatial variations across large areas (regional to global), but have fine temporal resolution for exchange processes. New model structures will be required for this linkage.

A number of ecological research teams are developing "generic ecosystem models" to investigate and contrast the likely responses of different terrestrial ecosystems to changes in the global environment over the next century. These models incorporate the important components, processes, and linkages present in all terrestrial ecosystems so that the intercomparisons can be made from a common perspective with the same units. Unfortunately, they are limited to present-day ecosystems and are therefore of limited usefulness for predicting responses to future global change. Linkage of generic

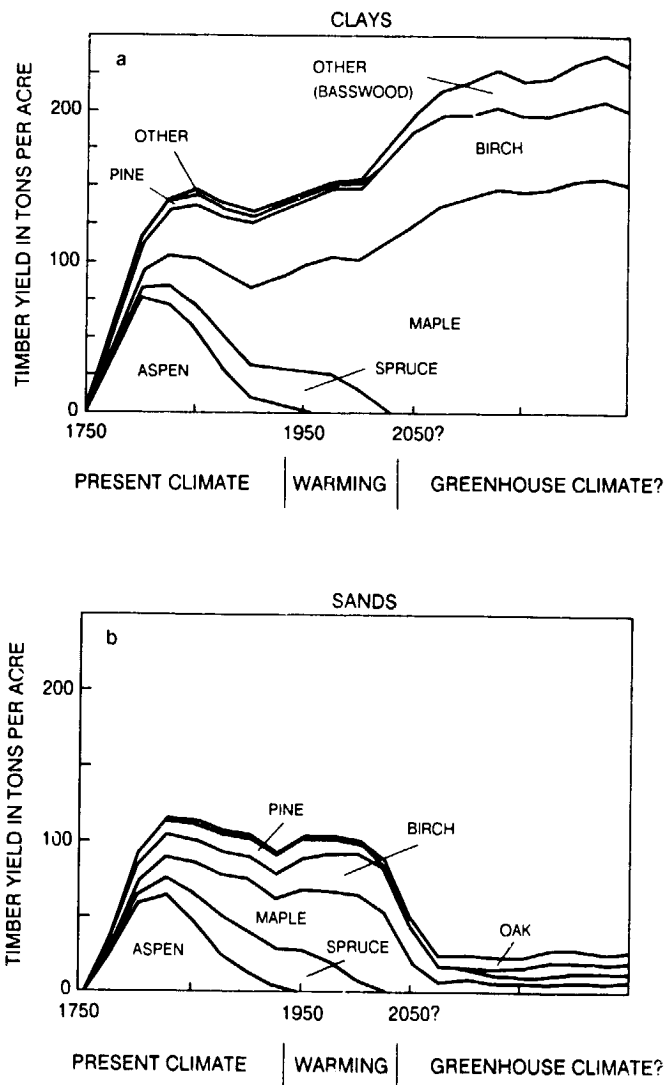


FIGURE 2 Predictions of biomass and species composition of Minnesota forests under climatic conditions predicted with  $\text{CO}_2$  doubling. The predictions are based on a population-based model that simulates forest growth, combined with a process-functional model that simulates soil moisture and nutrient cycling. Climatic inputs were the same for the two runs, but (a) simulates forest growth on fine-textured soils, and (b) simulates growth on coarse-textured soils. Note that biomass increases under greenhouse climate in (a), but falls to low levels in (b). Redrawn with permission from Pastor and Post (1988).

models to population-community models will be critical for long-term future predictions, or for regions where rapid rates of change occur. The resulting models should permit simulation of biospheric processes coupled to atmospheric and biogeochemical dynamics.

### **WHAT ARE THE TEMPORAL AND SPATIAL DYNAMICS IN RESPONSE OF ECOLOGICAL SYSTEMS TO GLOBAL CHANGE?**

Time lags in the ecological response to global change result not only from differences in longevity or life cycles among organisms, but also from nonlinear processes. For example, low availability of nitrogen, the most frequently limiting nutrient in terrestrial ecosystems (Pastor et al., 1984), may prevent ecosystems from changing in response to changing climate until after temperature thresholds are exceeded for dominant species. As previously dominant species are replaced by others, consequent changes in carbon and nitrogen cycles can happen rapidly, amplifying ecosystem response as illustrated in Figure 2 (Pastor and Post, 1988).

Time lags pose a challenge for the identification of cause-effect relationships, because due to delayed feedbacks, effects can be separated in time from causal events. Threshold effects from a slowly increasing variable (gradually increasing levels of ultraviolet radiation, for example) may prove difficult to distinguish from delayed responses to a single causal event. Experiments and models are needed to describe the time course of the complex series of responses that can occur in intact ecosystems. Paleorecords will be useful, especially where time lags are on the order of centuries. For example, pollen and paleolimnological records indicate rapid soil destruction in northwestern England at the time of the Younger Dryas cooling 10,800 years ago, but slower soil buildup following the rapid warming at the end of this event (Pennington, 1986).

Species differ in response times to environmental change, and different environmental variables lead to different lags among various species (Davis, 1984). Cumulative small changes (gradually decreasing rainfall) will have a different effect from changes in the frequency of discontinuous events (e.g., droughts). Indirect effects, such as enhanced growth due to demise of competing species, or due to increased nutrient supply resulting from changed microbial communities, complicate predictions of lag times. In general, rapid responses,

within a year, are seen in biotic factors such as microbial communities, plankton density, reproductive success of plants and animals, transpiration, photosynthesis and respiration rates, pathogen outbreaks, animal behavior, and densities of annual plants and short-lived animals. In the open ocean, biotic responses to climate are influenced by ocean currents and mixing, which track the seasonal cycle with a lag of only a few weeks. A lag time of several years or decades can be corrected in other processes, such as annual plant community structure, changed plankton density or net primary production caused by changes in consumers (e.g., insect epidemics and consumption of plankton by fish), and density and community structure of perennial herbs, shrubs, trees, and some animals. Moreover, changes in the genetic structure of populations depend on generation time. Whether redundancy within an ecosystem can delay responses of the system to environmental changes requires investigation, as this may be an important and perhaps unexpected influence of biodiversity on ecosystem processes.

#### **HOW WILL TRANSFERS OF MATERIALS ACROSS ECOSYSTEM BOUNDARIES BE AFFECTED BY GLOBAL CHANGE?**

The impact of climate change on the frequency of drought and other hydrologic events affects not only ecosystem-level processes but also related landform configuration such as the formation of deltas and changes in stream channels. Soil moisture influences vegetation physiognomy, which in turn influences albedo and surface roughness (Dickinson, 1986). Sediment loadings, types of particulate and soluble inputs, and flow rates can affect downstream terrestrial ecosystems and turnover rates, flow, and current dynamics in water bodies. Hydrologic dynamics dictate flooding, and thus affect wetlands formation, and gas emissions and nutrient exchanges under aerobic and anaerobic conditions.

Aeolian transport carries fertilizer and dust to adjacent or more distant systems. There is evidence that arid lands "feed" each other; i.e., they transfer materials in part because of similar biotic components and because of wind-driven particulate pathways. Long-range transport is important for global change, especially because this pathway may be crucial for quantifying the cycles of phosphorus and trace



elements. Stable isotope ratios provide a promising method for detecting origins of wind-borne particulates. Appropriate atmospheric models are now needed to simulate aeolian pathways.

In a related set of ecological processes, changes in climatic patterns will affect the distribution and/or intensity of fire, which is a major source of release of elements from terrestrial systems to the atmosphere. Thus models will need to incorporate these fire-driven processes into the description of aeolian transfers, especially as these transfers are related to changes in climate and land use.

Transfers across the biosphere-atmosphere interface will also be affected by global change. For example, changes that lead to alteration of wetting-drying cycles in seasonal wetlands, forest soils, and agricultural soils can alter the production and transport of biogenic gases (Harriss and Sebach, 1982), significantly influencing atmospheric composition and global biogeochemical cycles. Moreover, shifts between reducing and oxidizing environments can lead to changes in the relative quantities of trace gases such as  $\text{CH}_4$ ,  $\text{CO}_2$ ,  $\text{N}_2\text{O}$ , and  $\text{NO}$  released from the systems (Mooney et al., 1987). Likewise, major changes in the moisture characteristics of ecosystems change decomposition environments, e.g., from decomposition in anaerobic environments with subsequent release of  $\text{CH}_4$  to heterotrophic decomposition in aerobic environments, releasing  $\text{CO}_2$ . This example of a change in the decomposition pathway could be particularly important in northern bogs and tundra and could have significant impacts on atmospheric composition.

Global distribution of fluxes and their interactions should be studied using a combination of chamber estimates, aircraft in situ and remote sensing (e.g., LIDAR) measurements of gases, and eddy correlation techniques for estimating flux. These data should be collected and analyzed across gradients of moisture, temperature, or fertility, and used to develop and test models that describe the interacting nutrient cycles and fluxes. Data sets collected at multiple scales will facilitate development of models representing large areas.

In the marine environment, climate change and an increase in wind erosion are likely to increase the delivery of fine particles by aeolian transport from the continents to the surface waters of the ocean, where productivity could be affected (Martin and Fitzwater, 1987). Depending on their composition, such particles could have either biostimulatory or biotoxic effects on oceanic productivity and other marine processes. Another concern in the transport from land

to oceanic surfaces is the increase in nitrate, heavy metals, and aromatic hydrocarbons in precipitation as atmospheric pollutant loads increase from industrial sources.

Oceanic waters are currently a major source of dimethylsulfide (DMS) to the atmosphere. The oxidized products of this DMS add to acidic rain over continents downwind of oceanic sources, may increase cloudiness through nucleation on  $\text{SO}_4^{--}$  aerosols in the troposphere (Charlson et al., 1987), and may increase albedo in the stratosphere from  $\text{SO}_4^{--}$  aerosols (Ryaboshapko, 1983). Coccolithophorids are apparently a major source of DMS, and plankton processes clearly respond to mesoscale events and physical processes of a changing environment. Blooms and bloom conditions for these organisms can be observed through remote sensing of ocean color, sea surface temperature, and wind stress to document natural cycles of change in physical forcing and its biological response. The coccolithophorids are a special case, because in addition to chlorophyll the white light reflected by the calcite coccolith plates provides a unique signal that can be observed by satellite sensors (Holligan et al., 1983). Thus the potential exists to better understand the physical, chemical, and biological conditions associated with the onset and collapse of coccolithophorid blooms, and to make regional estimates of the ocean biogenic source for DMS.

Long time-series observations in oceanic regions are needed to document natural variability in physical forcing functions that contribute to seasonal and interannual variability in rates of primary production and the flow of this material through the marine food web. This information is necessary to formulate and refine hypotheses about how changes in the physical climate will affect plankton community composition and dynamics, and how these changes will feed back to climate via the residence time of photosynthetically fixed carbon in the sea. Two extremes with regard to carbon storage times can be envisioned. One might be the transfer of carbon from very small phytoplankton to protozoans and bacteria with a large fraction of the phytoplankton carbon respired to  $\text{CO}_2$  in a relatively short period of hours to days. Another would be the direct and rapid sinking of large phytoplankton cells, such as diatoms, to the deep ocean, with subsequent storage times for carbon on the order of decades and longer.

Coastal wetlands (salt marshes, mangrove swamps) are sources of several atmospheric sulfur gases (DMS,  $\text{H}_2\text{S}$ , COS,  $\text{CS}_2$ ). As sea level rises, the ability of wetland plants to oxidize their rhizospheres

could decrease owing to longer periods of inundation, increasing the flux of sulfur gases to the atmosphere. This hypothesis could be tested by examining the consequences of increased tidal flooding on wetlands currently experiencing subsidence, such as those in coastal Louisiana.

Freshwater wetlands, both natural (peat bogs, marshes, swamps) and managed (rice paddies), are major sources of atmospheric  $\text{CH}_4$  (Harriss et al., 1985).  $\text{CH}_4$  flux is the result of two competing processes— $\text{CH}_4$  formation and  $\text{CH}_4$  oxidation. Of the two,  $\text{CH}_4$  oxidation is much more temperature sensitive, increasing rapidly as temperature rises. Consequently,  $\text{CH}_4$  fluxes are greater when the temperature is lower. Increases in wetland areas in high latitudes due to increased precipitation could greatly increase the atmospheric  $\text{CH}_4$  flux.

An important component of the IGBP should be the study of estuaries and coastal regions that already experience high inputs of nutrients and other substances from terrestrial ecosystems. The resulting eutrophication is a growing problem of worldwide proportions. Inputs of both nutrients and pollutants to estuaries and coastal seas could change as climate affects rates of erosion and leakage of substances from terrestrial ecosystems. Primary production in many estuaries and coastal regions is limited by nitrogen (McCarthy, 1980), so potential nitrate outputs from terrestrial ecosystems receiving greater rainfall offer the possibility for significant enhancement of productivity.

### DOCUMENTING GLOBAL CHANGE IN ECOLOGICAL SYSTEMS

Documentation of past changes in ecological systems is necessary to demonstrate connections and cause-effect relationships within the global system. The record of the past, discussed in detail in the background paper on "Earth System History and Modeling," also provides a measure of natural variability before human-caused changes in the global system began. Observations needed to document future changes are equally important, and are discussed below.

Particular types of systems should be chosen for observation and study on the basis of their importance or their sensitivity and responsiveness. Ecosystems are important if either (1) they are large contributors to critical global cycles or (2) they are important as resources for human society. For example, oceanic waters should

be observed and studied because of their potential as sinks of atmospheric carbon dioxide and as sources of atmospheric DMS. Estuaries and nearshore ecosystems should be observed and studied because of their role as providers of fish, shellfish, habitat for wildlife, and recreational opportunities. Tropical forests are important reservoirs of biodiversity and play an important role in the global carbon budget, boreal wetlands are important sources of methane, and temperate grassland and forest regions are important for human food production.

Sensitive systems are easily changed and thus can be studied as early warning signals of global change. For instance, coral reefs in nearshore, tropical regions are sensitive to slight rises in temperature and relatively low levels of pollution (Hughes et al., 1987; Lessios et al., 1984; Loya, 1974, 1976b; Roberts, 1987), and temperate grasslands are sensitive to small changes in precipitation (Risser, 1985). Process and population dynamics studies are necessary to interpret changes in indicator species, and to separate natural variations from effects of pollution, temperature rise, or other parameters. Sensitivity has been determined primarily in reference to a particular impact, but the challenge to the IGBP is to consider the multiple causes—climate change, chemical loadings, direct human impacts—that can synergistically affect ecological systems.

Many transitional areas are either important globally or extremely sensitive to global change, e.g., the tundra-taiga transition (to climate change), the desert-grassland transition (which is undergoing direct human impact as well as being sensitive to climatic changes); and estuaries (areas of economic importance at the focal point of pollutant stress). Other examples are systems that have rapid turnover of nutrients, that have individuals or populations that may be characterized as sensitive to change, or that may provide an index of the effects of change. Indices to measure and monitor in these systems include productivity, distribution and growth rate of species with economic importance, changes in species that play an important role in the community or ecosystem, and in other key indicator species, distribution of structural types/forms of ecosystems, carbon pools and dissolved and particulate carbon losses, nutrient losses, and carbon:element ratios in foliage canopies.

An important criterion for choosing study systems is the potential for recovery and calibration of a paleoecological record of responses to past changes. Paleorecords of all types that indicate the

nature of past change in response to climate, human impact, and so on, provide valuable indices of sensitivity.

At each site chosen for long-term monitoring, responses to forcing factors should be studied through both empirical observations and experiments. The stations should be used to establish ground truth for satellite observation. The following aspects at the sites should be documented and understood:

1. Responses of individual species, especially key species that play major functional roles within communities, and distribution and abundance patterns of functional groups of species selected to characterize the response of particular systems should be studied.
2. Species interactions, including responses to pathogens and insect outbreaks should be investigated.
3. Ecosystem-level responses—especially those that feed back to the global system, such as biogenic gases, albedo, and moisture exchange and nutrient transfers among and between terrestrial and aquatic systems—should be studied.
4. "Indicator" species, gradients in physical conditions and/or biotic composition, or other parameters must be identified that can be observed easily (e.g., by remote sensing) and that respond rapidly, providing early warning of changes in the condition of ecosystems. The paleorecord may be utilized to identify aspects of the system that are sensitive to climate.
5. Changes in response dynamics should be studied in these particular systems to obtain better predictive capability for transient effects.
6. Spatial dynamics and sensitivities should be understood for the locality under study, including interactions with adjacent systems.

Because each system varies in its dynamics, variables to be studied will be different in each system. For example, in some systems the variable of interest is the influence of physical factors on net primary production, and in others, it might be sedimentation and gas exchange, how the food web partitions primary production, or how predators high on the food chain feed back on production. A long-term monitoring program is essential, to be combined wherever possible with a retrospective fossil record that reveals the trajectory of change before the onset of global change.

In addition to studies at individual sites, changes in the structure and function of biotic systems must be monitored on a global scale

to document future changes. Methods for monitoring terrestrial systems include calibrated multiband spectral absorptance of the earth's cover through time to provide information on such changes as biotic cover classes (Malila, 1980), net primary productivity (Tucker and Sellers, 1986), chlorophyll as an indicator of water quality in freshwater systems (Lathrop and Lillesand, 1986), and surface temperature (Mortimer, 1988). Still in the experimental stage but potentially useful for monitoring are changes in radar signal to provide information on the three-dimensional structure of vegetation indicating its successional status (Paris and Kwong, 1988) and changes in microwave signal analysis to derive surface properties such as flooded areas and soil moisture (Ormsby et al., 1985; Wang et al., 1986). Changes in human land use must be carefully monitored, especially in the tropics (Melillo et al., 1985).

Two strategies are being adopted by the Global Ocean Flux Study to make long time-series observations in oceanic regions that provide important steps in this direction. The first involves the use of satellite observations for ocean color that serve as a proxy for near-surface phytoplankton biomass. This provides an ocean-scale view of the pattern of plankton distribution, and how this changes in time. The second involves in situ observations at sites selected for their regional significance (National Research Council, 1984).

This latter approach will provide a framework of water column observations of physical, chemical, and biological processes in addition to rate measurements of certain processes such as primary production and the sinking flux of particulate material. The frequency of sampling and duration of these studies will be determined in the context of the processes that need to be studied at a particular site to improve our regional understanding of the coupling of ocean biogeochemical processes and the physical climate system.

Ongoing efforts to obtain global estimates of populations (e.g., large mammals, birds, and pathogens) to monitor biological reserves, water and air quality, and resources such as crops, forests, and fish, will provide valuable information for the IGBP. Of particular importance is increased attention to the assembly and analysis of existing data on large-scale temporal and spatial variation. Promising existing data sources include locality-specific data associated with museum specimens; the North American Breeding Bird Survey and Christmas Bird Counts; tree rings; data on censuses and distributions of the well-studied European biota; records of crop harvests taken

from the agricultural literature; paleoecological data; and written historical records.

A close coupling of process studies with the long-term observations will be required. The proper spatial and temporal scales for the long-time series observations and process studies will be determined by the specific question being asked. However, as a general strategy observations should be made along important environmental gradients, including gradients of physical turbulence, temperature, and pollution.

Ongoing programs relevant to the above include the World Ocean Circulation Experiment, Global Ocean Flux Study, Global Ecosystem Dynamics, and the U.S. National Science Foundation's Long-term Ecological Research network.

### PRINCIPAL ISSUES AND PRIORITY RESEARCH CHALLENGES

An important aspect of IGBP research is an understanding of the mechanisms of biotic response to global change. An understanding of functional processes is essential for predicting long-term and transient responses to circumstances that do not now exist anywhere on the globe. Both marine and terrestrial systems are highly variable in space, and marine biota in particular show great variability in time. The required research effort can be organized around several questions. How will biota respond to changes in forcing factors? What are the positive and negative feedbacks? And what are the effects on global processes if particular ecosystems or particular species are lost or drastically reduced in abundance?

Three research approaches should be used to increase our ability to predict biotic responses to global change and feedbacks to the global system:

1. Laboratory and field experiments at the organism level, and compilation of existing data on population and community patterns in response to environmental variation and land use patterns on large spatial scales, are needed. Field and growth-chamber experiments must quantify the responses of whole plants to temperature, moisture, carbon dioxide, and other forcing factors. These data are needed to understand global change and also to parameterize whole-plant ecological models. Features of plants and animals that influence their dispersal and successful invasion of new environments are important in predicting the time course of changes in vegetation

and in biodiversity in the face of global change. Fine-scale paleorecords of vegetation and faunal change will also be utilized. The genetic architecture of species and the way in which central versus peripheral populations will be influenced by rapid environmental change must be incorporated for realistic predictions. Invasions by alien species may provide a particularly valuable model for evaluating the response of species to new conditions such as alien predators, competitors, and pathogens. Existing data bases on plant and animal distributions and growth (e.g., tree rings) must be compiled for correlation with climate, land use, pollution, and other variables.

2. Experiments are needed on intact ecosystems, using large-scale manipulations and taking advantage of natural experiments. These large-scale experiments are necessary to expose intact ecosystems to changed temperature, water, nutrient levels, carbon dioxide, and pollution inputs, singly and in combination. Experimental approaches in terrestrial, lacustrine, and intertidal systems will include the use of portable greenhouses that enclose organisms and substrate and permit the monitoring of plants and soils under changed temperature, moisture, carbon dioxide concentration, and so on. Wetlands and upland watersheds can be subjected to hydrological manipulations and altered precipitation chemistry, and species of animals or plants can be introduced or subtracted from lakes or enclosed areas of landscape. Because of the inherently long lag times in ecological systems, responses must be monitored for many years (1 to 50), depending upon the particular processes in question. Population responses, system responses, and changed outputs to the atmosphere should be measured to parameterize models. The use of environmental gradients of temperature, salinity, nutrients, pollution, and human exploitation will be a powerful study approach.

In the oceans, natural experiments should be exploited that simulate conditions of global change. For example, regions of subsidence can be used to simulate the effects of sea level changes on tidal marshes or intertidal communities. In shelf areas, fish harvests alter the abundances of species, providing opportunities to study community structure. In the open ocean, eddies enclose water that is subsequently moved across major oceanographic meteorological fronts, providing a natural climatic change experiment. Anomalous years that change the position of the arctic front in the North Atlantic provide a means for studying the relationship between the extent of warm water and the mixing of nutrients. An international agreement should be made to ensure that in anomalous years, there



is capability for scientists to reach sites where changes in the physical environment are occurring.

3. In the long term, ecosystem models must be assembled that couple population-community models with process-functional models for simulation of the response of ecosystems to rapid, large changes in environmental factors. This combined approach will be used in the development of ecosystem models that are coupled with appropriate atmospheric models, to begin the process of developing sufficient understanding of linkages and feedbacks with the global system. These models should have predictive capacity for ecosystem responses to forcing factors, alone and in combination, predicting the biota for entire regions and describing consequent fluxes to the atmosphere and oceans.

Two critical problems arise in attempting to build a model that can be used to predict responses to global change. First, the variability of biological materials and the heritability of responses to environmental variation are inadequately known. Present models assume that all individuals are identical, but as more complex models are built, scaling up from single plants to landscapes and incorporating a spatial dimension, patterns of genetic variation must be incorporated. Second, the use of typological landscape or ecosystem descriptions (prairie, savanna) is inappropriate since global change may result in the development of new landscape or ecosystem "types" or biomes.

Element cycling and species composition of ecosystems are interdependent aspects of ecosystems linked by complex feedbacks. Changing species can influence element cycling via a number of mechanisms; similarly changing amounts or ratios of nutrient elements will influence species and community composition. Because of this, long-term models of ecological response to global environmental change must represent both process-functional and population-community aspects of ecosystems. Certain species play critical roles in ecosystems; if change is so rapid that these populations are killed outright, drastically changed or eliminated processes such as primary production, decomposition, and nutrient cycling will also respond. Prototypes of linked models exist to predict biomass and species composition with changes in climatic condition (see Figure 2; Pastor and Post, 1988). Substantial integration of observational, experimental, statistical, and modeling approaches will be required to generalize this type of representation for global application.

Once combined models are developed, they will then be coupled

with the next generation of atmosphere-ocean circulation models. Such combined models should be capable, for example, of predicting the following on a regional scale: net primary production, water-holding capacity of soil, albedo, surface roughness, canopy height, and trace gas production. Steps in the development of these models are as follows:

- Continue to develop whole-plant models of important plant forms (e.g., trees, grass, and shrubs) that incorporate carbon, nutrient and water exchange, and responses to the forcing factors, singly and in combination.
- Couple the whole-plant function model with population-community and ecosystem models to simulate ecosystem processes as affected by population change.
- Link the combined model with existing soil models, as has already been done for certain forest simulation models.
- Couple the resulting model with atmospheric models at the landscape scale (tens to hundreds of kilometers).
- Test the model over an appropriate range of systems, considering the effects of climatic change, changes in carbon dioxide concentration, precipitation chemistry and other forms of pollution, and so on.

Whole-ecosystem experiments will be relevant at all stages in the development of these models. The experiments will be necessary for the scaling-up of models from plants to ecosystems, and will also be used to validate models, to assess responses to multiple impacts, and to parameterize models. Similarly, the model development will suggest needed experiments and aid in their design. Validation of the incorporated processes can utilize the paleorecord of vegetation and hydrology as it responded to climate in the past. Fossil data have been compiled at a scale of resolution similar to general circulation models for Europe, eastern North America, and Japan, but additional records are needed, especially for Asia and for the tropics.

In order to develop and validate models, research sites are needed to test their specific predictive capacity. Research sites should be chosen on the basis of sensitivity to global change, importance via feedbacks to the global system, importance regarding human resources, the existence of ongoing studies that provide baseline information and background understanding, and the potential for developing and calibrating paleorecords that demonstrate responses to environmental changes in the past.

In summary, the initial priority for the IGBP is to obtain additional experimental data, so that new models can be developed to extrapolate ecological responses to environmental changes that have not been experienced in the past. Experiments to determine the response at organismal and community levels, as well as large-scale experiments directed toward scaling up from leaf to plant to stand to watershed to biome to global levels, are needed. Impacts from multiple stresses can be studied by means of fixed experiments on ecosystems. Natural conditions that expose entire systems to changes in environment that simulate some aspect of global change can also provide valuable information. Studies at specific sites are needed in order to develop the ability to predict changes in community and ecosystem structure, and to predict changes in fluxes of materials to the global system. Such sites need to be selected using a variety of criteria including sensitivity to global change, importance to the global system, relevance for society, and availability of background information about the system.

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## APPENDIX: PARTICIPANTS IN WORKSHOPS

### Working Group on Ecological Systems and Dynamics: Terrestrial Systems

January 12-13, 1988

Albuquerque, New Mexico

Margaret B. Davis, University of Minnesota, chairman  
Fakhri A. Bazzaz, Harvard University  
James H. Brown, University of New Mexico  
Linda B. Brubaker, University of Washington  
Stephen Carpenter, University of Wisconsin



William C. Clark, Harvard University  
Robert E. Dickinson, National Center for Atmospheric Research  
Pamela Matson, NASA Ames Research Center  
Michael B. McElroy, Harvard University  
Jerry Melillo, Marine Biological Laboratory  
Harold A. Mooney, Stanford University  
Gene Nainkoong, North Carolina State University  
Paul G. Risser, University of New Mexico  
David S. Schimel, Colorado State University  
Herman H. Shugart, University of Virginia  
Walter G. Whitford, New Mexico State University

**Working Group on Ecological Systems  
and Dynamics: Marine Systems**

February 18-19, 1988  
Cambridge, Massachusetts

Margaret B. Davis, University of Minnesota, chairman  
William C. Clark, Harvard University  
Robert E. Dickinson, National Center for Atmospheric Research  
John Edmonds, Massachusetts Institute of Technology  
Robert Howarth, Cornell University  
John Imbrie, Brown University  
Jane Lubchenco, Oregon State University  
James J. McCarthy, Harvard University  
Michael B. McElroy, Harvard University  
Brian Rothschild, Chesapeake Biological Laboratory

# Climatic and Hydrologic Systems

COORDINATOR: ROBERT E. DICKINSON

The climate system\* consists of many linked components, involving the atmosphere and its interactions with the oceans, land surface, cryosphere, and biosphere (see Figure 1). Various aspects of the hydrological cycle are important to all these components. The climate system and its manifestations in the hydrological cycle are central to the description, understanding, and prediction of the processes of global change.

Human activities are capable of producing large changes in the global climate system through massive alteration of the concentrations of radiatively active trace gases, especially  $\text{CO}_2$ ,  $\text{CH}_4$ , and the CFCs. The atmospheric concentrations of  $\text{CO}_2$ ,  $\text{CH}_4$ , and other important trace gases are maintained by biogeochemical cycles. Warming from an increase in radiative forcing, promoted by human activities, will alter the global distribution of temperature and moisture on time scales of at least decades to centuries and possibly over much

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A draft of this paper was prepared by committee member Robert Dickinson and revised according to comments received from a wide range of scientists (see the appendix to this paper).

\*The concept of the climate system was used initially by climate modelers in the early 1970s to represent this linked system. More recently, research on the physical aspects of the climate system has been organized internationally through the World Climate Research Program and within the United States through the National Climate Program Office.

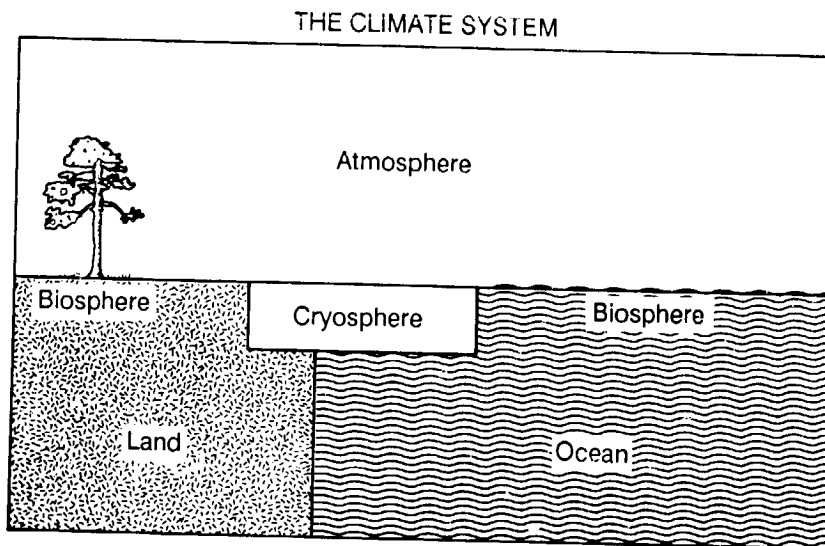


FIGURE 1 The climate system. Adapted from the National Climate Program Office's National Climate Program Five Year Plan 1988-1992.

longer time scales. Such changes will influence conditions for life over the earth. The detection and understanding of these changes are limited by an inadequate understanding of the natural variability of the system.

Figure 2 (Jaeger, 1988) shows a range of possible scenarios for global warming. The figure allows for emissions of all the trace gases affecting climate and for the delay of global temperature increase resulting from oceanic heat uptake. A narrowing in the uncertainty of the global average changes in the climate system is obviously needed. However, knowledge of such global averages alone is not very useful without an understanding of the actual change that will be experienced locally and regionally. A more complete picture requires understanding and predicting the regional manifestations of global climate change over time, with emphasis on changes in the hydrological system.

The need to improve and test climate models arises from the need for better descriptions both of present and past states of the climate system and of its natural variability. Documenting the changes within the climate system, using well-validated and well-calibrated climatic and hydrological observations, is an early goal for the global change program. New observational technologies will provide better

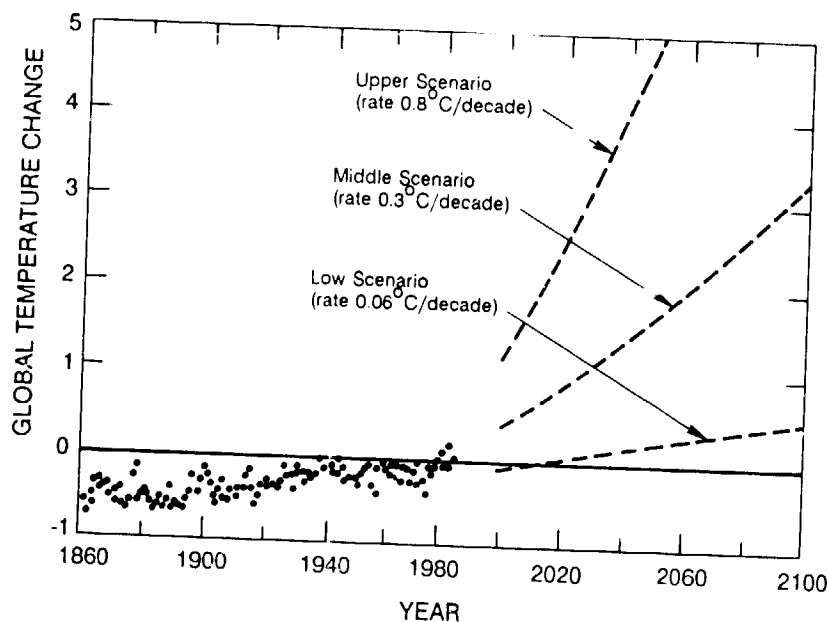


FIGURE 2 Scenarios of changes in globally averaged temperature that might develop in response to continued emissions of greenhouse gases. Values are plotted as differences from the 1985 value (Jaeger, 1988).

detailed descriptions and contribute to improved understanding of the complex global physical systems—the atmospheric, oceanic, terrestrial, and hydrologic systems including biota, snow, and ice. The exchanges of energy and water mass between these systems must be better described, quantified, understood, and predicted. Observations from space have provided, for the first time, the means to survey the many features of our planet rapidly, efficiently, and globally with high resolution using a single instrument or coordinated group of instruments. So revealing are these satellite-based investigations that they are now recognized to be indispensable for future research on the climate system.

At the same time, many important aspects of the system can only be studied through extensive observations made in situ. For example, element cycling between glacial and interglacial stages over the last 2 million years is particularly well recorded in the geological record. Isolation of the physical processes that drive these massive changes is a key ingredient for understanding the climatic system in

its present state and hence improving our ability to predict future climatic states.

Conceptual modeling and numerical simulations are and will continue to be powerful surrogates for and synthesizers of global observations. Elaborate data and information systems from the national level to the level of individual institutions are needed to combine information from various sources and from different federal agencies to describe the earth system as a related set of interacting processes, rather than a collection of individual components.

### CLIMATE FORCING FUNCTIONS

The climate system changes either in response to alteration of climate forcing functions (external forcing) or as a result of long-time-scale internal dynamics of the system (internal forcing). With respect to the dynamics of the total earth system, the only regular external forcing terms are solar radiation and the energy released by the decay of radioactive nuclides from the earth's interior. Episodic astronomical events such as collisions with large asteroids are very rare in the earth's history, but when they occur they can have drastic effects. With respect to individual processes, it may be convenient to regard also as external forcing the radiative effects of atmospheric constituents as well as those modifications of the land surface that change so slowly that they can be considered only weakly coupled to the climate system on the decadal time scale. However, for consistent predictions of the (long-term) evolution of the global system, biogeochemical forcing will have to be considered as an internal part of the system.

### Solar and Geological Forcing Functions

#### Solar Output and Orbital Variations

The radiative energy of the sun, centered in the visible and near-infrared wavelengths, serves through its differential input as the principal driver of atmospheric circulation. Thus radiative energy powers the climate machine. The march of the seasons is ample evidence for the acute sensitivity of the environment of the earth to changes in the distribution of solar radiation. A more sensitive gauge of the sun's impact on climate, however, is found in the Milankovitch effect, by which changes in the earth's orbit and axial orientation

provide slow and subtle changes in the latitudinal and seasonal distribution of insolation. These variations, far smaller than seasonal variations but of much longer period, serve to pace the recurrence of ice ages every 21,000, 41,000, and 100,000 years.

The solar irradiance has been measured accurately only since 1979. The small decreasing trend of 0.02 percent/year reversed in 1987, apparently with the 11-year solar cycle. For the period of observed decrease, the change in radiative forcing of the earth-troposphere system was comparable with, but opposite to, that arising from increasing atmospheric CO<sub>2</sub>.

Solar ultraviolet radiation, varying irregularly with solar activity, dictates the basic chemistry of the upper and middle atmosphere, including the equilibrium and composition of important trace gases such as ozone. Lightning is more frequent over continents than oceans, presumably as a result of the terrestrial concentration of ionization sources linked to soils and airborne dust. The global electric field is maintained by thunderstorm activity. Solar-induced variations in cosmic ray flux or changes in the efficiency of coupling between the solar wind and the high-latitude ionosphere may perturb it, with a possible but little-studied influence on climate.

Variations in solar radiation and particle fluxes have substantial effects on the magnetosphere and ionosphere, and solar irradiance variations and particle precipitation can affect the upper atmosphere. Variations in the abundance of cosmic rays alter the production rate for <sup>14</sup>C, which is the basis for much of the dating of records of past climate over the last 50,000 years.

### Volcanic Activity

Volcanic eruptions may inject into the stratosphere SO<sub>2</sub>, which can condense to aerosols and spread globally, thereby modifying radiative fluxes into the troposphere. Monitoring these aerosol clouds and documenting the climatic response can help the interpretation of trends in surface temperatures and contribute to an understanding of atmospheric transport properties. Individual large eruptions that have occurred since the beginning of the availability of global temperature records are known to have decreased global mean temperature by as much as 1°C for up to a few years. How great an effect might be possible from larger and/or more frequent eruptions is not known. The relatively uncommon eruption of a major caldera system could potentially have major, even if transient, influences on

global climate. Volcanism may provide varying amounts of  $\text{CO}_2$  over 10-million-year time scales.

#### Tectonic, Geothermal, Isostatic Rebound, Geomorphological, and Soil Changes

Tectonic modifications of continental positions and shapes on 10-million-year time scales are implicated in very large climatic changes. Past variations of tectonic and volcanic factors may help test our understanding of the climatic response to large forcing, both as a surrogate verification of climate model performance and for understanding sea level changes and their potential climatic connections.

The geothermal flow of heat from the earth's interior, an essentially constant boundary condition, supplements solar heating, albeit by only a small amount (1 part in  $10^4$ ). However, this heat source is significant for the thermal regimes of permafrost and ice sheets.

The response of the earth's lithosphere to loading and unloading of surface materials, including large ice sheets, sediments in deltas, and groundwater withdrawal, significantly affects regional sea levels. The response of bedrock to ice sheets has major implications for the dynamics of continental ice sheets.

The geomorphological processes that move, remove, or deposit soil and other sedimentary materials over the land surface modify the landscape and hydrological regime in significant ways. Rock weathering and soil formation processes, likewise, influence the land surface and are linked to biogeochemical cycles, especially the global carbon cycle. Wind-blown soil modulates atmospheric radiation and thus may contribute to regional climate.

#### Continental Ice Sheets

Continental ice sheets, currently those of Greenland and Antarctica have large effects on climate, especially in high latitudes. They also store much of the world's fresh water, and for at least the last 20 to 40 million years have been modifying sea level. Ice sheets normally change significantly in size only over time scales of several centuries or more. Their growth and decline, associated with changes in the earth's orbit and other causes, have produced past ice ages and interglacial periods.

### Orbital Changes

Changes in the earth's orbit and axial orientation modulate the latitudinal and seasonal variation of solar radiation and so apparently force a significant fraction of the glacial-interglacial fluctuation.

### Biogeochemical Forcing (Natural and Anthropogenic)

#### Carbon Dioxide

The concentrations of  $\text{CO}_2$  in the atmosphere have risen over the last century from 280 ppm to 350 ppm and are projected to continue to increase by 1 to 4 ppm/year over the next century. These increases in  $\text{CO}_2$  are derived from anthropogenic sources, primarily from the burning of fossil fuel and to a lesser extent from land use changes, e.g., the clearing of forests.  $\text{CO}_2$  concentration also depends on what fraction of  $\text{CO}_2$  release is taken up in the oceans (about half) and what is taken up or given off by soils and vegetation (a considerably smaller fraction) versus the fraction that remains in the atmosphere. Increasing  $\text{CO}_2$  elevates greenhouse heating by about  $6 \ln(n/n_0)$  in  $\text{W/m}^2$  (where  $n = \text{CO}_2$  concentration,  $n_0 = \text{preindustrial values of } \text{CO}_2 \text{ concentration}$ ,  $W = \text{watts}$ , and  $m = \text{meters}$ ). Atmospheric  $\text{CO}_2$  provides the carbon for growth of vegetation; thus changing  $\text{CO}_2$  modifies this growth.

Changes in the chemical, biological, and physical characteristics of the oceans, vegetation, and soils in response to changing climate will provide a climate- $\text{CO}_2$  feedback. A warmer climate may reduce the capacity of the upper ocean to store  $\text{CO}_2$ ; it may also enhance both photosynthetic uptake and respiratory release of  $\text{CO}_2$ . At present, we do not know the sign, let alone the magnitude of this feedback. The variations of atmospheric  $\text{CO}_2$  with glacial cycles (inferred from data in polar ice caps) suggest the presence of such feedbacks.

#### Methane

The concentration of  $\text{CH}_4$  has risen from preindustrial values of less than 0.8 ppm to current concentrations of about 1.7 ppm, adding about 0.5  $\text{W/m}^2$  of warming to the global climate system. Since the atmospheric lifetime of  $\text{CH}_4$  (about 10 years) is short in comparison with the time scale of changes in its concentration, shifts in its concentration reflect changes in the balance between sources



(mostly biological and anthropogenic) and destruction (mostly by OH radicals in the atmosphere). Past increases over the last century are ascribed largely to increases in CH<sub>4</sub> sources associated with human activities in agriculture, forest clearing (biomass burning), and fuel exploitation, transport, and consumption. Nevertheless, the role of past and future changes in rates of CH<sub>4</sub> destruction in the atmosphere also warrants careful scrutiny. Changes in temperature, inundation period, and inundation area will change CH<sub>4</sub> flux from natural wetlands and permafrost regions. There may also be substantial release of CH<sub>4</sub> from methane hydrates present in continental slope sediments as the ocean responds to atmospheric warming.

#### Dimethylsulfide

Cloud droplets form around cloud condensation nuclei (CCN). Oceanic clouds primarily condense around sulfate aerosols, which are supplied by DMS emitted by the oceans (Charlson et al., 1987). DMS is generated by certain kinds of marine phytoplankton, and its generation rate may depend on the temperature of the ocean surface waters. An increase in sulfate CCNs would increase the numbers of cloud droplets and hence increase planetary albedo over the oceans. We need to better quantify how the flux of DMS now influences cloud cover and albedo and how various changes might modify the flux of DMS to the atmosphere.

#### Other Aerosols

Aerosols of both natural and anthropogenic origin, e.g., from desert dust or conversion of combustion products, may modify radiative fluxes either directly by their radiative properties or indirectly through their effects on cloud cover or optical properties. Lifetimes of aerosols depend on wet and dry deposition processes, which may vary with climate change.

#### Other Trace Gases

The CFCs F-11 and F-12 may in several decades also build up to large enough concentrations to add significantly to greenhouse warming. Likewise, N<sub>2</sub>O, tropospheric and stratospheric O<sub>3</sub>, and to a lesser extent many other trace gases are also of radiative importance and are undergoing changes in flux rates. Changes in climate and hydrology will feed back on production and destruction rates of

these trace gases. In particular,  $O_3$  decrease and  $CO_2$  increase can reduce stratospheric temperatures by large amounts and so affect the planetary wave and radiative coupling to the troposphere. Stratospheric water vapor is strongly dependent on the temperature of the tropical tropopause and on  $CH_4$  concentrations.

### Effects of Land Use Changes on Climate

Changes in agricultural activities, deforestation, and desertification are increasingly affecting the climate system and in turn are affected by changing climate. The impacts of vegetation and land use changes on climate are of two kinds:

1. Biogeochemical: surface modifications affect global atmospheric composition and its radiative balance. Biomass burning, a major mode of deforestation, is a source of  $CO_2$ ,  $CH_4$ ,  $N_2O$ , CO, particulates, and other trace gases. Deforestation is generally accompanied by degradation of soils and enhanced fluxes of  $CO_2$  and  $N_2O$  to the atmosphere. Increases in rice cultivation and ruminant population increase the amounts of  $CH_4$ , while an increase in fertilizer usage contributes to rising  $N_2O$  concentrations in the atmosphere.

2. Biogeophysical: modifications of vegetation cover alter regional hydrology and regional surface-energy balance. The importance of land-surface effects on climate has been suggested by modeling sensitivity studies. These studies indicate that increases in albedo from land degradation in semiarid regions could promote drought. Other studies have shown that model-simulated climates are also sensitive to land-surface boundary conditions that affect evapotranspiration. Interactions between vegetation and snow cover may also be important.

The issue of realistically modeling how land processes, in particular vegetation and soil moisture, interact with the climate system is only now beginning to be addressed. Such modeling should recognize the two-way coupling between these two systems, as vegetation changes both its form and its function in response to climatic forcing. The modeling efforts must recognize the small spatial scales over which vegetation cover and soils vary.

## RESPONSE OF THE CLIMATE SYSTEM TO CHANGES IN FORCING

### Nature of Climatic Forcing

Changes in total solar output, stratospheric aerosol, or atmospheric trace gases that are long-lived (fairly well mixed globally), such as  $\text{CO}_2$  and  $\text{CH}_4$ , affect the climate system through the additional global radiative forcing that they provide. Some differences occur in the vertical, latitudinal, and seasonal distribution of atmospheric radiative forcing, but the effects of these differences are not yet established and are apparently relatively small. Thus studies of the global response of climate to increases in atmospheric  $\text{CO}_2$  also largely apply to increases of other trace gases and to increased solar heating. The practical question is thus how the climate system responds to the sum of various global inputs in the past and future.

The change in climate from changes in global radiative forcing will be in part manifested by a variety of regional responses, with changes in some regions more significant than those in others. Changes in other climate forcing factors, in particular those related to vegetation and ice cover, will have their largest effects on a regional scale and be specific to the given forcing and location. These effects largely involve changes in energy exchange processes at the surface, especially over continental interiors.

### Key Areas of Uncertainty in Evaluating Climate System Response

#### Cloud Effects

Clouds have multiple properties that are important for climate change. They modulate both incoming solar radiation and outgoing thermal infrared radiation. Reflection of solar radiation depends not only on cloud amount but also on the optical thickness of clouds, on the liquid water content of the clouds, and on the size distribution of the cloud droplets. The upward flux of thermal infrared emission from clouds depends on cloud-top temperature and on cloud emissivity. Only high, thin clouds, i.e., cirrus, have emissivities that are significantly less than 1.0 and hence have thermal emission controlled by cloud thickness.

Preliminary and incomplete treatments of cloud feedback on climate have been included in recent GCM studies of climate response

to CO<sub>2</sub> doubling. These studies have found that cloud changes significantly affect the surface temperature response. As temperatures increase, clouds are expected to hold more liquid water and hence be more reflective, thereby reducing the warming significantly. In the case of cirrus, however, increased amounts of thermal infrared radiation are expected to be trapped and so amplify the greenhouse warming. Unfortunately, these effects have not yet been included in GCM simulations of climate change. Different GCM simulations have shown qualitatively similar spatial patterns in the longitudinally averaged cloudiness change; they indicate, in particular, a decrease in cloudiness in the moist, convectively active regions such as the tropical and middle latitude rain belt and an increase in the stable region near the surface from middle to high latitudes as well as in the lower stratosphere. Such cloud changes would be expected to have significant regional effects on radiative balance and hence surface temperature.

Actual clouds are often thinner than a model layer and generally have horizontal scales of 1 to 100 km, i.e., scales unresolved by the grid of global models; hence, their radiative properties may not be correctly modeled. Thus we need appropriate data bases and a conceptual and statistical framework for describing the morphology of realistic cloud fields made up of clouds of various shapes and sizes. Also required is an understanding of the radiative, dynamical, and microphysical processes determining this morphology. Diurnal variations of cloudiness are poorly characterized but are probably significant for determining changes in cloud radiative balances and land surface evapotranspiration feedbacks.

The net global feedback is even more difficult to model than the regional effects of cloud changes. Cloud processes in models need to be related through observations to other meteorological processes. The primary line of evidence that actual cloud feedbacks are not extremely far from what is modeled is the reasonable success of global models in reproducing seasonal and diurnal cycles of the global climate system.

#### High-Latitude Response

The largest regional temperature increases from global warming are expected in high latitudes as a result of albedo and atmospheric stability changes linked particularly to the extent of sea ice. Modeling

studies find that most of the high-latitude temperature increase occurs in winter as a result of increased summertime uptake of heat by the oceans through an increased fraction of open water and thinner sea ice and a corresponding wintertime release of that heat.

The annual growth and decay of sea ice introduce a strong seasonal signal not only to the physical but also to the biological components of the polar regime and may affect ocean uptake of  $\text{CO}_2$  and nutrient supplies. Treatments of these issues have been handicapped by inadequate consideration of the complex effects of sea ice dynamics, ice distributions at subgrid scale, and interactions with ocean dynamics and salinity and with overlying cloud cover. Also, polar regions, especially in winter, are relatively poorly represented by global climate models because of their low absolute concentrations of water vapor and the singular aspects of the poles in spherical coordinate systems.

Processes determining albedos of snow and ice are linked to many other components of the system. Changes in permafrost have large effects on the land surface and hydrological regimes. Increases in summer temperature and thaw period may enhance photosynthesis and respiration of boreal forests as well as  $\text{CH}_4$  production by high-latitude peat lands.

#### Atmospheric Hydrological Response

Water vapor is the most variable radiatively active constituent of the atmosphere and is the main contributor to the greenhouse effect of the atmosphere. In addition, even slight changes in the water mixing-ratio and corresponding changes in relative humidity can alter the density, optical properties, and altitude of clouds and hence affect the transfer of solar and terrestrial radiation through the troposphere. A rise in global tropospheric temperature increases atmospheric water vapor, which in turn increases by approximately twofold the rise in surface temperature from the other greenhouse gases alone. However, this feedback is rather uncertain because of lack of understanding of possible changes in water vapor concentrations, especially in the upper troposphere and lower stratosphere.

Global circulation models simulate the very broad-scale features of global precipitation reasonably well, including the main bands of precipitation along major depression tracks and in the tropical rain belts and the areas of meager rainfall over major deserts and along the eastern side of the subtropical oceans. Nevertheless, there are

serious errors on the regional scale, and patterns and amounts of precipitation vary from model to model. Even the degree of error is difficult to judge because of major uncertainties in measurements. In the long term, the radiative cooling of the atmosphere is balanced globally by latent heat release resulting from net condensation and the transfer of sensible heat from the surface. Thus simulated precipitation rates are sensitive to the parameterization not only of precipitation processes but also of radiative and turbulent transfer of heat from the underlying surface.

At the low horizontal resolution of current global models, the simulations of sharp features such as the tropical rain belts and frontal systems are smoothed. The orographic effects of mountains and ice sheets are poorly treated. The high spatial variability of rainfall patterns, especially those connected with convective systems, presents serious challenges both to estimation of rainfall amounts and to the modeling of variations of the surface-hydrologic system over land. Statistical representations of rainfall structures as now used in studies of catchment hydrology need to be related to atmospheric processes and incorporated into climate models.

Improved algorithms for simulating the movement of water vapor, sensible heat, and momentum through the planetary boundary layer are important for modeling the coupling between the atmosphere and the land and ocean surfaces.

### Surface Hydrological Response

The terrestrial hydrology is forced by atmospheric phenomena, i.e., precipitation, surface radiative balance, surface winds, air temperature, and humidity. The land in turn interacts with the atmosphere through fluxes of sensible and latent heat. Key constraints on these interactions are the conservation of energy and water, and these constraints must be included in even the simplest treatments. However, actual land surfaces are extremely complex, and models are only now being developed that capture some part of this complexity.

Surface hydrological processes, i.e., runoff, infiltration, and evaporation, depend on the soil, vegetation, and the aspect and slope of the land surface. These processes appear to vary over a wide range of spatial scales. The parameters entering into the descriptions of these variables in models are inferred from local measurements of processes made in specific environmental settings. Precipitation is initially intercepted by canopy foliage; that which reaches the ground

percolates downward, according to soil-and moisture-dependent hydraulic conductivities. Water is returned to the atmosphere either by evaporation from the soil surface or by evapotranspiration from the surfaces of green leaves.

The movement of water through plants depends on plant physiology, in particular leaf stomatal functioning, which is not always easily modeled. These physiological processes interact with atmospheric gases. For example,  $\text{CO}_2$  concentrations are known from laboratory studies to have a large immediate effect on the stomatal resistance of many plants. However, adjustments that may occur over the lifetime of plants or in future generations that may compensate for such effects are poorly known. Roots that move water from soil to plants can provide the limiting resistance to evapotranspiration under conditions of water stress.

The rate of evapotranspiration is proportional to differences between the water vapor concentrations at or just within soil and plant surfaces and the water vapor in the overlying air. The vertical structure of vegetation coupled with the complexities of turbulent transfer processes within and immediately above the canopies complicates simple flux-gradient modeling. The vapor gradients driving fluxes of water from soil and vegetation surfaces depend in turn on surface temperatures, which themselves depend crucially on the processes determining the surface energy balance.

Climate models that are used to simulate future climate change from increasing trace gases have not yet incorporated detailed models of hydrological processes. However, simple energy- and moisture-conserving parameterizations for soil moisture have resulted in an indication of possible future hydrological change. In particular, some model results suggest a significant decrease in soil moisture in middle latitudes of the Northern Hemisphere during the summer season. This summer drying could arise from a northward shift in the mid-latitude summer rain belt and from a greater and more intensive period of drying associated with earlier snowmelt and warmer temperatures. Decreases in cloud cover may amplify this midcontinental drying, raising the specter of a possible future increase in the frequency and severity of agricultural drought in central continental areas of the mid-latitudes. Forest fires and dust storms also must be considered as potential agents of land surface change. The water supply for mid-latitude arid regions, mainly derived from mountain winter snowpack, is poorly represented in current models of climate change, where resolution is too coarse to resolve the topography of

individual mountain ranges and their critical effects on precipitation. Treatments of runoff in climate models do not adequately represent the realities of catchment-scale hydrology, such as the highly non-linear, almost threshold, relationships between rainfall and runoff as well as the dependence on terrain, soil heterogeneity, and subgrid-scale statistical structures of rainfall patterns. The hydraulic conductivity of soils, determining the rate of water infiltration, can be strongly controlled by biological processes that influence, for example, soil structure and macropores.

Improvements in modeling the linkages between surface hydrology and climate require better understanding of evapotranspiration from diverse terrestrial vegetation, other land covers, and lakes; infiltration of water through the unsaturated zone with consequent improved understanding of aquifer recharge; the conversion of precipitation to streamflow, including the role of topography at a variety of scales of catchment and storm patterns; and the processes of snow accumulation, transformation, redistribution, and melting.

#### Ocean Coupling to the Rest of the Climate System

The ocean is coupled to the atmosphere through exchanges of sensible, latent, and radiative heat; momentum; various important trace gases, e.g.,  $\text{CO}_2$  and DMS; and the exchange of water by precipitation evaporation and river flow from the land. The temperature of the ocean surface is especially important in determining these fluxes. Surface temperatures in turn depend not only on these fluxes but also on the redistribution of thermal energy within the oceans by vertical mixing and by horizontal energy transport, i.e., the oceanic general circulation. The ocean circulation is in turn sensitive to the supply of fresh water and consequent changes in salinity. Oceanic heat uptake will affect the transient evolution of both global temperature increase and changes in regional hydrological properties. In high latitudes, the presence and seasonal variation of sea ice constitute another important oceanic climate factor that couples to atmospheric and oceanic energy exchange processes and can substantially enhance the response of high-latitude climate to radiative forcing.

The ocean, through its intermediate-time-scale circulations, is capable of changing the equilibrium concentrations of  $\text{CO}_2$  on relatively short time scales. The possibility of multiple circulation states of the ocean leads to the possibility of multiple states of the climate



system. Exchanges of nutrients between land and ocean and oceanic nutrient cycles may also have climate feedbacks.

### Abrupt Change

Observationally, an abrupt change is one that is rapid in relation to the time and space resolution of direct or proximate measures of change. Considerations of past and future climate change have been dominated by the assumption that any gradual forcing would elicit a smooth response. However, an increased understanding of the global climate system and its complex feedback processes suggests the possibility of changes that come in steps rather than occur gradually. For example, records from ice and ocean cores, and conceptual and numerical models, suggest that the Atlantic Ocean could have more than one mode of circulation. Abrupt transitions between these modes might be triggered by variations in salinity of the high-latitude oceans caused by changes in river flow, glacial melt water, sea level, precipitation, or evaporation. Other features of oceanic circulation, which in turn strongly affect the rest of the system, may shift abruptly in response to slow shifts in atmospheric circulation and rainfall patterns. Large increases in the frequency or intensity of El Niño Southern Oscillation events in the tropical Pacific might occur. These events have a major influence on rainfall patterns, especially in the tropics, and on oceanic circulations that determine nutrients for marine productivity. Disappearance of year-round arctic ice cover because of greenhouse warming might be accompanied by significant changes in high-latitude climate.

The large lake systems that existed in the Great Basin of the western United States about 13,000 years ago almost completely disappeared within a few hundred years, suggesting that a rapid and discontinuous change occurred in the overall behavior of the surface hydrologic system for a region covering about one-half million square kilometers. Other, perhaps speculative, abrupt changes include the collapse of the west antarctic ice sheet, catastrophic  $\text{CH}_4$  release from destabilization of  $\text{CH}_4$  clathrates in the Arctic, a rapid destruction of the Amazon forest regional climate system, and a discontinuous change to a colder and less disturbed stratosphere in the Northern Hemisphere that is accompanied by a large decrease in high-latitude stratospheric  $\text{O}_3$ . Where there are large gradients, e.g., in the tropical rainfall distribution, climatic shifts imply large changes in regional climates.

Some or all of these possibilities appear rather unlikely over the next century, but their consequences could be much more severe than those of gradual global warming. Thus there is a clear need for scrutiny of evidence in the climatic record for abrupt climate change and its effects on the system from natural causes. Careful observation of the current system and studies with joint ocean-atmosphere models of the climate system that may exhibit multiple equilibria are needed to better understand the prospects of natural and human-induced abrupt change. The links between planetary radiation, atmospheric trace gas content, atmospheric water transport, ocean circulation, and the marine and terrestrial biospheres also need to be examined with this possibility in mind.

#### **DOCUMENTATION OF PRESENT CLIMATE AND THE FACTORS THAT CAUSE IT TO CHANGE**

The following key research issues should be addressed:

1. The recovery of the past history of environmental change, involving studies of ocean and lake sediments, ice cores, tree rings, and sea level changes for information about past climate, hydrological regimes, ocean circulation, biological interaction, atmospheric chemical composition, and solar inputs.
2. Comprehensive documentation of changes in the current physical environment, including observation and understanding of the sun and near-earth space, the atmosphere, snow and ice, oceans, and the soils and vegetation of the earth.

The former aspect is discussed in the companion paper on "Earth System History and Modeling," and the latter is discussed below.

Only within the last few decades have the technology, telecommunications, and the logistics necessary to handle large amounts of data been developed to the point where comprehensive global observations of the climate system have become feasible. Sustained progress in understanding the global system will require a comprehensive continuous observing program, ongoing theoretical investigations, and global modeling efforts. Such a program is necessary to document climate changes, to further studies of important processes, and to provide the data needed to construct, test, and utilize models of the system and its components. Some limited instrumental data extend back over a century or more and provide much of what is now known about past change. Such data must be analyzed and their

collection extended into the future, with considerable care for the continuity and calibration of these records.

Most studies of the current global atmosphere now rely on the information provided by the worldwide network of surface and upper-air sounding stations organized by the World Weather Watch and the system of four to five geostationary and two polar-orbiting meteorological satellites, which has been, more or less, in operation since the Global Weather Experiment of GARP (about 1979). This real-time operational observing and data management system is complemented by various sources of delayed data such as temperature profiles of the upper oceanic layer, sea level data, and a wide variety of surface and subsurface hydrological measurements. The system suffers from several deficiencies, which include (1) serious gaps in the three-dimensional distribution of wind observations over the oceans; (2) large uncertainties, resulting from insufficient sampling and measurement errors, in the estimation of precipitation over land areas and total lack of information over the oceans (and over some countries that do not make hydrological data available for international exchange); and (3) significant uncertainties in the three-dimensional global distribution of water vapor and clouds, and the almost total lack of global information about surface properties, including soil moisture. Climate studies are concerned with the quality and continuous availability of the data, whereas the real-time collection is primarily of importance for operational agencies.

Current prospects for the geostationary platforms of the system are satisfactory, since the major meteorological satellite operators are now in the process of finalizing their plans to replace some of the existing operational satellites with a second generation of spacecraft with nearly identical advanced sensors. However, the replacement of existing operational environmental satellites in polar orbit must be undertaken to ensure the continuity of essential atmospheric measurements as well as to provide adequate facilities for testing experimental remote sensing instruments.

The measurement of the distribution of all phases of water in the atmosphere should be given high priority if the fundamental role of fresh water on time scales of decades to centuries in all subsystems of the earth system is to be understood. Global patterns and amounts of precipitation on a year-to-year basis must now be estimated by the use of rain gauge networks over land coupled with correlations of precipitation with cloud top temperatures over oceans. A Tropical Rainfall Measurement Mission would begin to satisfy a

critically important requirement for direct space measurements of global precipitation by testing the feasibility of using active and passive microwave data together with visible and infrared imagery. A low-inclination orbit could resolve the mean diurnal cycle of rainfall over the tropics and assess the relationship of latent heat released into the atmosphere to anomalies in atmospheric circulation.

Studies of atmospheric water vapor are also equally important. Its variations in space and time are inadequately known. Planned improvements of operational satellite instruments should start soon to yield significant information for the lower troposphere on a global scale. Atmospheric radiation balance is especially sensitive to the concentrations of water vapor in the upper troposphere and lower stratosphere.

Radiative balance of the climate system, and the dynamical processes that give rise to cloudiness, are highly significant for climate. Continuous measurements of the total solar output provide a fundamental boundary condition for radiative inputs, as do measurements of the varying contribution to planetary albedo from stratospheric aerosols. Current analyses of cloud amounts and their trends are based upon visual estimates by ground-based observers. The International Satellite Cloud Climatology Project (ISCCP) now under way will assemble a 5-year data set of radiance measurements from information returned by five geostationary and two polar-orbiting satellites. The data will allow compilation of meaningful statistics for cloud amount, type, height, and optical thickness. The First ISCCP Regional Experiment (FIRE) is a U.S. contribution helping to validate algorithms for this derivation. Global information on the altitude of cloud bases is not included in these measurements, but is also needed.

A complementary approach to determining the role of clouds in the radiation balance is the measurement of the components of the radiation balance itself: the fluxes of solar and infrared radiation at the top of the atmosphere and their inferred value in an equivalent cloud-free environment. The difference is the "cloud forcing." This quantity is obtained using a combination of a simple, wide-field-of-view instrument on sun-synchronous polar-orbiting satellites together with non-sun-synchronous satellite measurements of the Earth Radiation Budget Experiment (ERBE). Spectral and directional models are necessary to relate the narrow-spectral-band, narrow-field-of-view operational instruments to the total fluxes and

to infer the fluxes at the top of the atmosphere from those at satellite altitude.

The International Satellite Land Surface Climatology Project (ISLSCP) program, through such field programs as the Hydrological Atmospheric Pilot Experiment (HAPEX) in 1986 and the First ISLSCP Field Experiment (FIFE) in 1987, focuses on the development and improvement of algorithms for remote sensing of physical properties of the land surface important for climate models. Progress has been made in the observation and interpretation of a vegetation index based on the difference in reflected radiances in the visible and near-infrared channels of the Advanced Very High Resolution Radiometer (AVHRR) imager and, more recently, in another approach to a vegetation index based on a microwave measurement. Also promising are procedures to measure surface radiative temperature, including its diurnal variations, from window infrared and microwave thermal emission and procedures to obtain incident surface radiation from reflectance of visible radiation by clouds. Progress in inferring surface albedo is also being made, with improvement in atmospheric corrections including cloud removal, better calibration, and advances in understanding the angular dependence of bidirectional reflectance of land surfaces.

Observation from space of land surface climate properties requires considerable information about the atmosphere. First, radiative emissions sensed from the surface are modulated by atmospheric gases, clouds, and aerosols, whose effects must be quantified. These modulating influences can be as important as the land properties being measured, both for the dynamics of the land processes and for the climate system in general. Second, some key observations such as the indirect measurement of soil moisture, hence evapotranspiration, require measurements of near-surface atmospheric properties, e.g., humidity and winds. A detailed description of surface-energy balance over land, like that over the ocean, requires both atmospheric and surface information.

Observational research on land surface climate processes and hydrology must be closely coordinated with related meteorological studies, such as those of the U.S. National STORM Program, and with global change activities in the areas of biological dynamics and biogeochemical cycles. Besides satellite systems, there will be a need for continued application and development of aircraft measurements, in situ sounding systems, and surface instrumental systems, especially for process studies. These land surface climate processes are

linked to the many practical facets of the impacts of climate change, e.g., water resources and agricultural productivity.

Changes in glaciers and small ice caps, in both high-latitude and mountain environments, contribute to global sea level rise and fall. Seasonal snow is another sensitive indicator of climate change and provides positive feedback through its effect on global albedo. The presence of sea ice, already measured from space, completely changes the magnitude of the heat and moisture fluxes from the ocean as well as the surface albedo. High spatial resolution of measurements is important to determine the fractional ice-covered areas in regions of broken ice. Large thermal fluxes can be associated with these marginal ice zones. Additional measurements are needed of sea ice thickness, the distribution of ice of differing ages and its motion, and the extent of surface melting and its relation to ice albedo.

A change in the volume of polar ice could result from an increase or decrease in global temperatures. Yet at present we have no reliable means to assess changes in the inventory of ice in the Greenland and antarctic ice sheets. We need to know whether present ice sheets, averaged over the seasonal cycle, are in steady state, growth, or decay phases. Variations in polar ice volume should be detectable in sea level measurements, but these data are noisy and influenced by the thermal expansion that results from global temperature change, by local tectonic movements, and by rebound from the melting of the last major glacial ice sheet. Ground-based surveys are not definitive, but satellite altimetry could be applied to this problem.

Current observational programs in the ocean sciences support the goals of the IGBP to the extent that they focus on ocean surface temperatures and how they might vary with climate change, and on how the oceans store and exchange radiatively important trace gases. Surface temperatures are linked to vertical mixing and convection processes and depend on vertical distributions of temperature and salinity, horizontal advection of these quantities, and hence ultimately on the oceanic general circulation.

Complementing the sparse data coverage by the many ship-based programs, satellites provide regular global observations over the ocean of surface temperatures, sea ice cover, and in the future, wind stress from roughness, winds over the ocean, and sea level height. It is necessary to measure the geoid more accurately in order to use sea level heights to derive ocean surface currents. Long-term monitoring of sea level height is needed both from surface and from space platforms.

## PRINCIPAL ISSUES AND RESEARCH CHALLENGES

### Sustained, Calibrated, Long-term Measurements

Long-term monitoring of the more important global climate and hydrological variables is crucial. This objective requires stable, well-calibrated measurements over a multidecadal time frame. Monitoring of both forcing functions and system responses is needed. The list of long-term monitoring needs cited in NASA's Earth System Science Committee (1988) report (here reproduced as Table 1) merits full support. The most critical forcing variables are solar irradiance, volcanic emissions, and radiatively important trace species, especially CO<sub>2</sub>, CH<sub>4</sub>, and the CFMs. Atmospheric response variables of highest priority for long-term measurement are surface air temperature, tropospheric temperature, precipitation, and surface pressure. Also very important are winds, especially in the tropics, components of the earth radiation budget, cloud amount, type, height, and optical thickness.

Land surface properties for a variety of representative surfaces must also be measured over a long term, especially those properties controlling the fluxes of water between surface and atmosphere. These properties include precipitation, measures of soil moisture, and vegetation cover, all on a regional scale. Measurements must include the surface radiative temperature, incident solar flux, seasonal snow cover, snow water equivalent, changes in the volume of high-altitude and continental ice sheets, amount of river runoff, distribution of permafrost, levels and freezing dates of lakes, extent and seasonality of wetlands, and other surface characteristics such as albedo, roughness, and emissivities in the infrared and microwave bands. Key ocean variables are sea surface temperature; sea level; sea ice extent, type, and motion; ocean wind stress; subsurface circulation; and incident solar flux. *Adequate attention should be given to sustained, calibrated, long-term measurement of the types of variables discussed above and analyzed by NASA's Earth System Science Committee.*

### Information Systems

Components of information systems include data transmission, quality control, directories, catalogs, and inventories; products of special analyses; status of data observation, collection, archiving, and distribution; and agreements for international exchange of data.

TABLE 1 Sustained, Long-term Measurements of Global Variables Important for the Study of Global Change on Time Scales of Decades to Centuries (NASA's Earth System Science Committee, 1988)

Variable	Importance	Analysis Product Quality
<b>External Forcing:</b>		
Solar irradiance	***	A
Solar constant	**	B
Index of volcanic emissions	*	D
<b>Radiatively and Chemically Important Trace Species:</b>		
CO <sub>2</sub>	***	A
CH <sub>4</sub>	**	A
O <sub>3</sub>	**	B
Chlorofluorocarbons	**	A
Tropospheric O <sub>3</sub>	**	C-
CO	**	D-
Stratospheric O <sub>3</sub>	***	C
Stratospheric H <sub>2</sub> O	**	C
Stratospheric NO	*	C
Stratospheric H <sub>2</sub> O	*	C
Stratospheric HO <sub>x</sub>	*	C-
Stratospheric aerosols	**	B
<b>Atmospheric Response Variables:</b>		
Surface air temperature	***	B
Tropospheric temperature	***	B
Stratospheric temperature	**	C
Pressure (surface)	***	A-
Tropical winds	**	C-
Extratropical winds	*	B
Tropospheric water vapor	**	D
Precipitation	***	C-
Components of Earth radiation budget	**	B
Cloud amount, type, height	**	D
Tropospheric aerosols	*	D
<b>Land-Surface Properties:</b>		
Surface radiating temperature	*	F
Incident solar flux	*	C-
Snow cover	*	C
Snow water equivalent	*	F
River runoff (volume)	*	B
River runoff (sediment loading)	*	D-
River runoff (chemical constituents)	*	F
<b>Land-Surface Properties:</b>		
Surface characteristics (topography, roughness, infrared and microwave emissance)	*	C-
Index of land use changes (broad classification of vegetation types)	**	F
Index of vegetation cover	***	D
Index of surface wetness	*	F
Soil moisture	***	F
Bioextent, productivity, and nutrient cycling	***	F
<b>Ocean Variables:</b>		
Sea surface temperature	***	C
Sea ice extent	**	B
Sea ice type	*	D
Sea ice motion	*	C-
Ocean wind stress	***	C
Sea level	**	D
Incident solar flux	*	D
Subsurface circulation	***	C-
Ocean chlorophyll	***	C-
Biogeochemical fluxes	**	C
Ocean CO <sub>2</sub>	**	C

## KEY

Importance (for documenting and understanding global change)

\*\*\* Essential    \*\* High    \* Substantial

Analysis Product Quality (presently available multi-year global analyses)

A = Good quantitative, well calibrated

B = Well discriminated, absolute accuracy doubtful

C = Useful, poor discrimination

D = Qualitative index, interpretation doubtful

F = No information

- = Not global coverage

Policies for pricing of data and funding for acquisition must encourage, rather than hinder, the required research and analysis with long-term multidecadal data bases. Calibration and long-term stability of operational measurements must be adequate to ensure the integrity of the long-term data bases. Plans must include adequate programs for reanalysis of model-assimilated data bases.

Special attention is needed to develop systems to handle the large data streams from present satellite observations and the even larger ones from future coordinated packages as planned by NASA in its EOS program. The analysis of these data into forms readily



manageable by the scientific community will be a key issue. Large amounts of information must be made available to the scientific community in a friendly, supportive, and timely fashion, through distributed systems using modern computational (supercomputer) and workstation technologies. *An aggressive and supportive new approach at the national level is needed to develop a national data and information system for climatic and hydrological data that is consistent among agencies and thus allows ready access by a wide variety of researchers.*

### Hydrological Cycle

Understanding the cycling of water in its three phases is crucial for studies of global change. Within the atmosphere and at the surface, water absorbs and reflects solar radiation with a wide range of albedos. Both clouds and water vapor are more important for transfer of thermal infrared radiation than any of the trace greenhouse gases. Evaporation removes much of the net radiative heating at the earth's surface; vertical and horizontal transport of water vapor is a dominant mechanism for redistribution of energy within the atmosphere. Water is a key ingredient of tropospheric and stratospheric chemical processes. It is also critical for the presence of life. In particular the dynamics of terrestrial vegetation, through its dependence on water supply from precipitation, are linked to climate.

Current information on the global and regional budgets of water is inadequate, and key ingredients—i.e., clouds, atmospheric water vapor, soil moisture, precipitation, and evaporation—are now inadequately measured. These variables and the processes responsible for them need to be better represented in global models. The World Climate Research Program (WCRP) has developed a concept of a Global Energy and Water Experiment (GEWEX) to greatly improve the observational and modeling basis for including the physical hydrological system in studies of global change. *Building upon the GEWEX concept of WCRP, a program should be developed to better define the hydrological cycle and related energy fluxes by means of global measurements of observable atmospheric and surface properties, and to study and model processes of the global hydrological cycle and its connections to land processes and properties of the oceanic surface layers.*

### Effects of Terrestrial Vegetation on Climate and the Hydrological Cycle

There are close connections between climate and vegetation cover of both natural and managed ecosystems. The global patterns of net radiation, ocean temperatures, and precipitation impose strong constraints on the dynamics of vegetation. However, there are also significant feedbacks of the vegetation cover on the climate system. Important factors controlled by vegetation include surface albedo, evapotranspiration, and surface roughness. These factors are still poorly represented in global climate models. They depend in part on the changes of vegetation cover with seasonal temperatures and associated extreme weather events, and on variations in precipitation processes, seasonal or otherwise. They also depend on atmospheric composition either as a stress factor or as a source of nutrients, e.g., the dependence of evapotranspiration on atmospheric  $\text{CO}_2$  either directly through its control of stomatal closure or indirectly through its control of ecosystem structure. *A program of observations and modeling should be developed to improve understanding of the effects of terrestrial vegetation on climate and to build a foundation for incorporation of these effects in models of global climate change.*

### Sources of Biogenic Gases and Dependence on Climate

Some biological processes contribute to greenhouse warming by changing atmospheric composition. Other processes provide condensation nuclei for clouds and so may contribute to an increased cloud albedo, hence a cooler climate.  $\text{CH}_4$ , the next most important greenhouse gas after  $\text{CO}_2$ , is poorly understood as a factor in global change. We do not know why it has increased by more than a factor of 5 since the last ice age, and we cannot predict how either terrestrial sources or atmospheric loss might be modified by changes in climate or atmospheric composition. DMS is apparently the major source of cloud condensation nuclei over the oceans; yet we have no idea as to how its sources might change with climate change. *A program of observation and research is needed to improve understanding of the sources of atmospheric gases from biological processes and to develop parameterizations for including these sources in coupled models of global climate change and biogeochemical cycles.*

### Atmospheric Dust and Aerosol

Solid particulates in the atmosphere affect atmospheric radiation balance directly through their modulations of atmospheric radiation balance and indirectly through their role as cloud condensation nuclei. Atmospheric aerosols either increase or decrease the net absorption of solar radiation, depending on their optical properties and those of the underlying surface. Carbon particles are generally the most absorbing, and pure sulfate particles the most reflective. Wind-suspended material originating in arid regions is widespread and has been recorded in vastly increased amounts in the paleoclimatic record. Its representation in climate models would help focus on the transport characteristics of the models (also needed for coupled chemistry studies) and would add representation of a significant ingredient in the climate system. *Research is needed to describe the surface processes responsible for the lifting of soil and desert aerosol on a global basis, the distribution of this aerosol within the atmosphere, its global transport and locations of deposition, and the inclusion of all these processes within a global climate model.*

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# The Human Dimensions of Global Environmental Change

COORDINATOR: WILLIAM C. CLARK

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This paper was compiled by committee member William C. Clark based on several recent meetings on the topic and comments from a large number of experts in the social science community. See Annex B for detailed description of the process by which this paper was prepared.

## INTRODUCTION

The need to view human activity as an integral component of the geosphere-biosphere system has been emphasized since the earliest writings on global change. The Russian mineralogist Vladimir Ivanovich Vernadsky, recapitulating in 1945 themes he had first articulated in lectures and books 20 years earlier, described his concept of

the biosphere, the only terrestrial envelope where life can exist. Basically, man cannot be separated from it. He is geologically connected with its material and energetic structure. (Vernadsky, 1945)

Echoing the Italian geologist Stoppani, Vernadsky argued that the most environmentally significant aspect of the human connection was not technology per se, but rather the sense of global knowledge and communication engendered by that technology.<sup>1</sup> He portrayed this "noosphere" or "realm of thought" as

a new geological phenomenon on our planet. In it for the first time man becomes a large-scale geologic force. Chemically, the face of our planet, the biosphere, is being sharply changed by man, consciously, and even more so, unconsciously. (Vernadsky, 1945)

Vernadsky and his predecessors had neither the data nor the instrumentation to convert their insights into useful analytical tools for describing and understanding global interactions between environment and processes of human development.<sup>2</sup> Over the last 50 years, however, and especially in the quarter century since the International Geophysical Year, the necessary measurements, models, and concepts have rapidly accumulated. We now know that human activities have fundamentally transformed the face of the earth, as well as the diversity and distribution of its biota. These activities

<sup>1</sup>Stoppani, writing in 1873, argued that man constituted a new geological force, and designated ours as the "anthropozoic era." He believed that "the creation of man . . . was the introduction of a new element into nature, of a force wholly unknown to earlier periods. It is a new telluric force which in power and universality may be compared to the greater forces of earth." (*Corso di Geologia*, Vol. ii, cap. xxxi, sect. 1327 Milan).

<sup>2</sup>For example, despite their seminal character and originality, both the work of George Perkins Marsh (1964) and, nearly a century later, the first major interdisciplinary review of *Man's Role in Changing the Face of the Earth* (Thomas, 1956) are ultimately anecdotal works that infer a global assessment on the basis of experience in a relatively small number of intensely studied areas.

have induced chemical fluxes at the continental and even global scale that are comparable to or greater than those occurring in nature. They have long since changed local climates and may now be altering the heat and water fluxes of the entire planet (Bolin and Cook, 1983; Holdgate et al., 1982; Nriagu and Pacyna, 1988; Turner et al., in press).

The reciprocal impacts of environmental change on human societies have also become significantly clearer over the last half-century. Simplistic theories of environmental determinism have been replaced by an increasingly sophisticated appreciation of the ways in which the physical environment shapes the challenges and opportunities that face communities, regions, and states (Chisholm, 1982; White, 1988a). The possible implications of global environmental change for sustainable human development are beginning to be appreciated (Clark and Munn, 1986; Jacobs and Monroe, 1987; Milbrath, in press; Redclift, 1987; WCED, 1987). Still needed, however, is a research paradigm that takes Vernadsky's insights seriously and that harnesses the full range of scholarship necessary to address the *interactions* among human, ecological, and physical systems involved in global change.

Understanding the interactions between human and environmental systems demands involvement of many fields, including resource and development economics, political science, sociology, geography, human behavior, anthropology, history, law, and engineering. Applied assessments of environmental impacts, risk, and hazard also provide insights. And numerous works have examined the human causes or consequences of particular instances of large-scale environmental change.<sup>3</sup> In addition, a growing interest in the human dimensions of global change has elicited over the last several years a number of symposia, workshop reports, and edited volumes (see Annex B).

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<sup>3</sup>Specific examples of this work are cited in the text of this paper. But no comprehensive and critical review of this material has yet been conducted with a view towards its relevance for global change studies. An excellent initial survey is provided by White (1988b). Among the broadest critical assessments of major studies on particular environmental problems is Glantz et al. (1982).

### Goals for Research on the Human Dimensions of Global Change

The need for an interactive view of global change has been recognized in the IGBP since its inception. The initial exploratory symposium on global change at the 1984 ICSU General Assembly in Ottawa included several papers under the general heading of "the geosphere-biosphere and human activity" (Clark and Holling, 1984; Kates, 1984; Revelle, 1984). As articulated by Robert Kates at ICSU's 1984 Ottawa symposium on global change:

[t]he research opportunity over the next decade is to examine the boundaries of the sustainable development of the earth. Basic scientific research will provide much improved knowledge of human-induced change in the biosphere, the capacity of natural systems to absorb such change, and the ability of human societies to adjust or adapt their behavior. The focus will be on the convergence of problems, methods, and theory. From such fundamental knowledge a scientific and truly human ecology can emerge and it should be part of an international geosphere-biosphere program. (Kates, 1984:493)

Two years later, the program was defined to include the objective of understanding the manner in which the earth system is influenced by human actions.

ICSU's Special Committee for the IGBP broadened this goal to include the reciprocal consequences of global change for resource availability as an underlying theme deserving special emphasis in the program (ICSU, 1987:3-4). The question is, therefore, not whether, but only *how* the interactions between environmental and human systems should be studied in the context of the International Geosphere-Biosphere Program.

### Goal and Organization of This Paper

The goal of this paper is to articulate the principal issues and questions that should be addressed to assure effective integration of research on the human dimensions of global change within the U.S. contribution to the IGBP.

This is an intentionally restrictive goal that explicitly excludes many important aspects of the interactions between environment and society. In particular, this chapter does not purport to lay out basic research agendas for the individual social or behavioral sciences or engineering disciplines with interests in environmental change.



Such agendas can only be defined "internally" by the specific fields involved; a number of efforts are now under way to do just that. Nor does this chapter attempt to address the immediate policy issues of what to do about global change. Again, other initiatives are actively investigating such questions.<sup>4</sup>

The essence of such an "external" definition of priorities is that it cannot be made by any one discipline. Indeed, it highlights questions that lie at disciplinary interfaces, and that must be resolved for the understanding of global change per se. In that spirit, this chapter attempts to focus attention on aspects of the human dimensions of global change in which the interactions with environmental systems are of central importance.

In support of this objective, the chapter proceeds from a general discussion of relevant themes to some specific suggestions for research on the human dimensions of global change. In particular, the following section presents a broad overview of the principal elements involved in humans' interactions with the global environment. Some of the major unresolved questions regarding the character, causes, and consequences of those interactions are then summarized in the section on "unresolved questions," drawing upon the previously noted body of recent discussions on the human dimensions of global change. Many of these questions will be dealt with through the normal course of research now planned or under way in a number of countries and disciplines. In addition, however, the problems discussed in that section pose a number of especially complex and interdisciplinary research challenges that might best be addressed as part of the formal U.S. contribution to the IGBP. Five such research challenges are highlighted in the final section of this paper as a stimulus to further and fuller discussion in the course of IGBP planning efforts.

### **PRINCIPAL ELEMENTS OF THE HUMAN SYSTEM INVOLVED IN GLOBAL CHANGE**

This section outlines the elements of the human system that

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<sup>4</sup>In addition to the studies listed earlier as contributing to this report, a number of other explicitly discipline-oriented and solution-oriented groups have begun to examine the human dimensions of global change. To encourage exchanges among such groups, a partial listing with addresses is provided in Annex A.

require special attention in studies of global change. Three basic dimensions of the human role in global change are discussed: the interactions between human and environmental systems; the choices that individuals, governments, and other organizations make in efforts to alter or manage those interactions; and the underlying elements of social structure or culture that shape both interactions and choices.

Within this framework, focus could be sought in a number of ways. Experience with interdisciplinary studies in general and environmental impact assessment in particular argues strongly for the approach adopted below. This starts with interaction, attempts to identify the most important ways in which human and environmental systems influence one another, and then tries to determine which social structures and processes are most important in explaining those interactions.

### Interactions

The most basic elements of the interactions between human and environmental systems are suggested in Figure 1. The figure reflects the central fact that both the human and the environmental systems of the earth change in response to their own internal dynamics, to external perturbations over which neither exerts appreciable control, and to their interactions with one another. Two forms of interaction are of central importance for the purposes of this chapter. The first concerns the sources of environmental change that result from demographic, economic, institutional, technological, agricultural, and behavioral changes in the human system. The second concerns the consequences for human well-being that result from climatic, chemical, and biotic changes in the environment system. The temporal and spatial scales at which important interactions between human and environmental systems occur require special attention in efforts to define a focused research agenda on global change.

### Sources

In principle, human processes drive global change by altering the flows of energy and materials among components of the geosphere-biosphere system (Orians, in press). In practice, the most important sources of alterations involve the following:

- the release of "pollutants" as varied in their effects as DDT, carbon dioxide, and nuclear radiation;

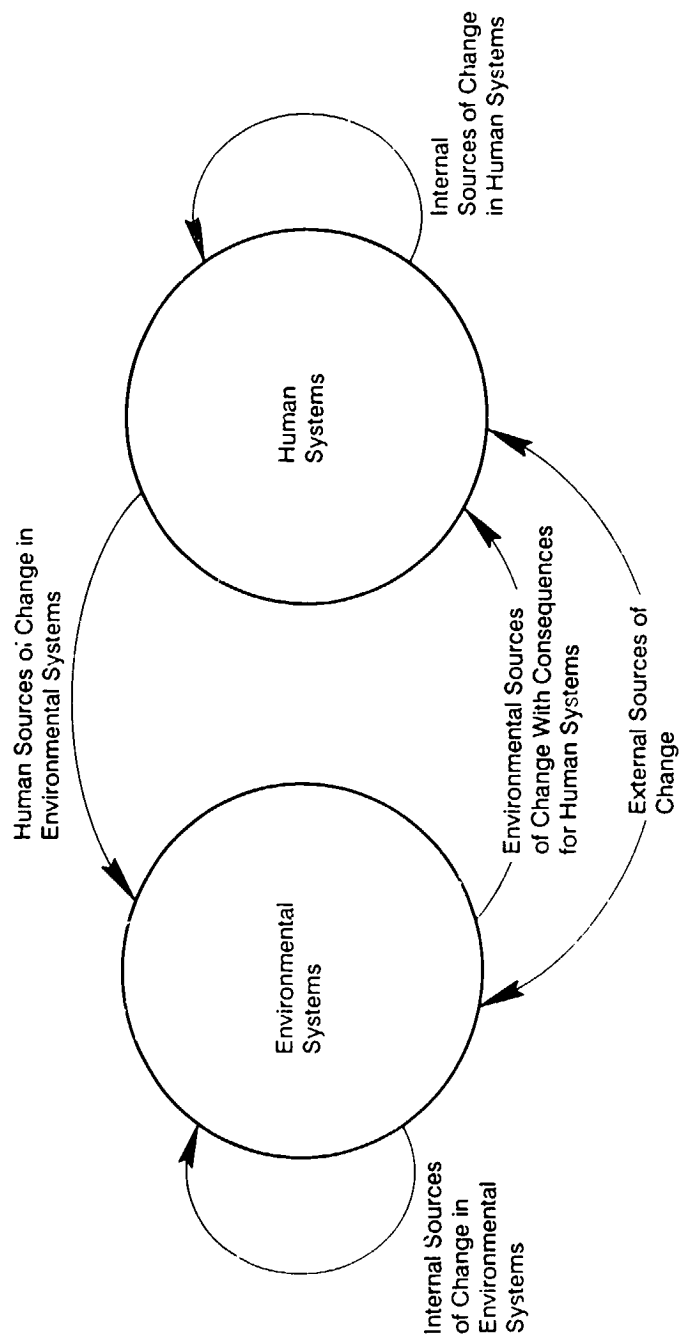


FIGURE 1 Interactions between human and environmental systems.

- the sequestering or redistribution of other materials and energy ranging from phosphorus to soil organic matter to running water;
- the direct transformation of physical structures (e.g., terracing), surface properties (e.g., albedo), and habitats (e.g., wetland drainage);
- the direct removal of species from the biotic system through harvest, the direct addition of species to the system through transport from other areas ("invasion"), or low- and high-tech versions of genetic engineering ("domestication"); and
- interactions among the above.

The human activities that have contributed most importantly to these sources of global change include agricultural and industrial production, and energy consumption (Bolin and Cook, 1983; Clark and Munn, 1986; Turner et al., in press). Within these broad categories, there is a need to identify which specific activities are most significantly implicated in existing global environmental changes, and which additional activities might become implicated in the future.

### Consequences

Research on the human consequences of environmental change has established that the degree of threat experienced by a society is a function of four interactive variables: risk, exposure, vulnerability, and response (Kasperson and Kasperson, 1988; Kates et al., 1985; Kotlyakov et al., 1988; Whyte and Burton, 1980).

In terms of the framework presented here, risk is defined in terms of the actual or estimated changes in selected environmental variables. One of the clearest lessons of environmental impact studies is that assessments are ineffective if they seek to develop comprehensive lists of all environmental risks affected by human activity. More useful have been studies that focus on a modest number of "valued environmental components" (Beanlands and Duinker, 1983). These are simply attributes of the environment that people choose to value. Which components are valued in any particular situation will depend on many of the considerations of scale, choice, and culture discussed below. Scientists, policymakers, and other interests must negotiate the valued environmental components that merit priority attention in assessing the risks posed by global change.

Notions of social vulnerability are central to understanding the

human consequences of global change (Timmerman, 1981). Individuals and societies can cope with a wide range of environmental changes, but at different costs and within different limits. Studies of human response to natural hazards, climate change, and nuclear war show that both costs and limits change with time and are mixed functions of the environment itself plus the underlying demographic, organizational, and developmental characteristics of the human system as discussed later in this chapter (Burton et al., 1978; Harwell and Hutchinson, 1985; Parry et al., 1988). Some tentative generalizations have begun to emerge. But a general understanding of social vulnerability to environmental variations remains a distant if urgent goal.

Differences in the exposure of various social groups and geographical regions to globally distributed environmental changes severely complicate both expert and lay assessments of environmental threats. Recent work on "total exposure assessment" to air pollutants has shown how misleading broad average exposure estimates can be (e.g., Ott, 1985; Smith, in press; Spengler and Soczek, 1984). Concepts relating to heterogeneities in exposure and empirical estimates of such exposures will be central elements in an understanding of the human dimensions of global change (e.g., Vaupel and Yashin, 1986).

The human choices that constitute societies response to global change are reviewed later in this paper.

### Scale

As noted earlier, studies of global change need to devote particular attention to interactions that become significant on temporal scales ranging from decades to centuries and spatial scales ranging from large regions to the globe as a whole. These are much coarser scales than those at which most research on human systems has focused. On the other hand, many aspects of long-term global change have their primary sources and consequences at relatively fine scales (Holling, 1986; White, 1988a). Moreover, notions of sustainability are strongly dependent on the linkages among regions simultaneously exposed to global environmental change. Coupling observation and explanation across multiple scales therefore becomes a central requirement for understanding global change (Risser, 1986; Rosswall et al., 1988).

A long tradition of attention to space and time dimensions in

geography, economics, and history has produced a relatively sophisticated view of the difficulties involved.<sup>5</sup> This experience shows that much confusion and unproductive debate results when scholars working at different temporal or spatial scales contrast unlike situations without recognizing the problems and limits of transference (Chisholm, 1982). In order to minimize such problems in efforts to understand the human dimensions of global change, a first requirement is the explicit identification of what scales are involved in each effort to document or explain specific interactions between environmental and social systems. Beyond this, it is important to know which human processes are likely to interact most strongly with the environment at the coarse (decadal and regional) scales that are central to global change. Initial studies suggest that special attention should be given to global, long-term studies of topics such as the life cycle dynamics of major industrial processes, fuel substitution in energy systems, urbanization, labor absorption in the agricultural sector, and the conditions limiting the extent of major crop zones (Clark, 1987). Finally, understanding is needed on the ways in which certain fine-scale phenomena of human systems (e.g., technical innovations) cascade "up-scale" to yield consequences significant for global change.

### Choice

A fundamental asymmetry in the interactions between human and environmental systems does not appear in Figure 1, but is nonetheless essential to an understanding of global change. For while the response of environmental systems to human activities is entirely reactive, the response of human systems to changes in the environment has both reactive and proactive elements. Human behavior can respond not only to actual environmental changes that have already occurred, but also to people's perceptions and assessments of possible future changes that they hope to encourage or avoid. This reflexive or anticipatory potential of human systems raises the prospect of

<sup>5</sup>Economists have devoted extensive attention to what Thomas Schelling (1978) has called the connections between "micro motives and macro behavior." Geographers have made significant progress in understanding connections between individual human actions and regional environmental consequences at the level of the landscape (Kotlyakov et al., 1988). And historians are increasingly pursuing comparative, transnational approaches to the study of long-term global interactions between people and their environments (Richards, 1986).

conscious environmental management. It also focuses attention on the central role that studies of human choice and behavior must play in efforts to understand global change.

The central position of choice behavior in the interactions between human and environmental systems is suggested in Figure 2, which draws heavily on research concerning the human ecology of natural and technological hazards. One important aspect of that research is its treatment of choice behavior as a potential modifier of both the human sources and the human consequences of environmental change. Another is its recognition that virtually all human choices relating to environmental change entail a significant degree of risk taking and uncertainty, and thus almost inevitably result in a significant degree of surprise (White, 1988b). Coupled with broader studies in the behavioral sciences, decision analysis, and policymaking, the research on hazards suggests that three factors play significant roles in shaping human choices relating to environmental change: values, options, and perceptions.

### Values

Values, in the present context, can be viewed as an indication of what people think they want from the interactions between human and environmental systems. Research has shown strong associations between positive valuations of the environment and concrete behaviors that sustain environmental systems (Darley and Gilbert, 1985). Conversely, a strong argument has been made that most human choices that degrade the global environment are governed by values that weight short-run benefits to people over long-run damages to the environment and the foundation for sustainable resource development that it provides (Bandura, 1986).

The important roles of human values in the interactions between people and the environment are rapidly changing, as reflected in the tremendous expansion and strengthening of the environmental movement over the last quarter-century (White, 1988a). At the local level, this shift can be seen in the explosive growth of environmental groups for self-help and neighborhood action around the world. At the national level, political parties have begun to give environmental issues central places on their agendas. Expenditures for environmental protection have grown to constitute 1 or 2 percent of the GNP in most industrialized countries (Holdgate et al., 1982). At the international level, the evolving position of environmental values is reflected

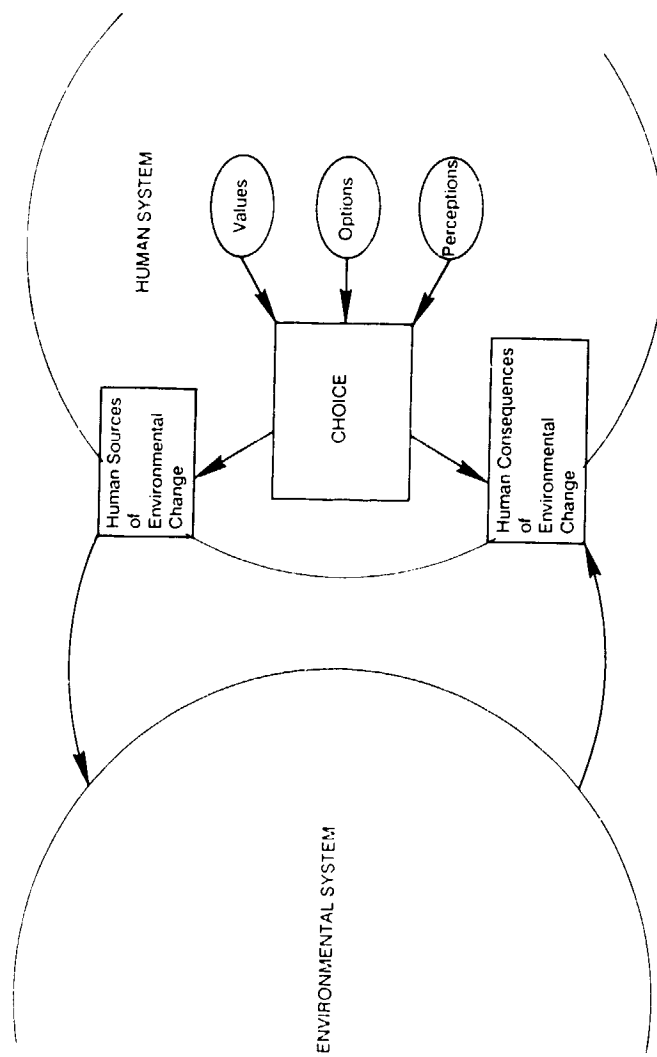


FIGURE 2 The role of choice behavior in the interactions between human and environmental systems. This figure is based on a model of human choice and environmental perception proposed at the China-U.S. Workshop on the Human Dimensions of Global Change (Tang and Jacobson, 1988), and causal structure of hazard management proposed by Hohenemser et al. (1985; Figure 11).



in successive reports of special U.N. World Commissions. Whereas commissions formed earlier in this decade had dealt with security or development issues in isolation, the Brundtland Commission's 1987 *Our Common Future* report emphasized the connections among environment, development, and security and stressed the need to pursue all three objectives in concert (WCED, 1987).

Which values are most relevant to global change? Classic economic notions of efficiency are clearly no longer the dominant values guiding many of today's decisions that are seen to have an environmental component. Increasingly important are values reflecting alternative conceptualizations of development, a sense of stewardship for the planet, and obligations to future generations or other neglected populations (White, 1988a). How such values are factored into environmental choices, how they enter government processes, and how their character and reach vary over time or among cultures, are central to an understanding of global change.

### Options

If values reflect what people want, options reflect what they can get. Clearly, not everything people value can be obtained; what can be obtained may often be reached via alternative paths. Moreover, the value and option dimensions of choice are related. Research on policymaking has shown that people generally decide what they want only in light of what they think they can get (March and Olsen, 1976; Wildavsky, 1979). Reciprocally, what they can get at any given time often reflects options developed in response to previously unobtainable desires.<sup>6</sup> Not surprisingly, one of the greatest contributions that formal analysis actually makes to practical policymaking is through enlarging the range of options available for choice (Schelling, 1983).

The options involved in human choices concerning global change can be grouped in three interrelated categories: technological, organizational, and economic. Technological options concern the alternative ways in which basic processes of resource use, manufacturing, service provision, and waste control can be carried out. Examples

<sup>6</sup> A relevant but neglected body of work on the mechanisms of this process has accumulated under the rubric of "induced innovation" studies. For overviews, see Binswanger and Ruttan (1978), Ruttan (1984), and Runge (1986).

range from selective harvest versus clear-cutting for forest management, to fossil versus nuclear sources of electrical energy. Organizational or institutional options range from basic modes of social structure, through alternative regulatory arrangements, to various legal structures. Examples include market vs. control economies, pollution permits versus effluent taxes, and international versus regional treaties and conventions. Finally, a focus on economic options emphasizes the fundamental requirement that societies be able to afford choices undertaken in pursuit of their values. While maximizing efficiency may not always be an appropriate criterion for choice, even the most ardent conservationists are coming to realize that environmentally sustainable development must be economically sustainable as well (Madden, 1987; WCED, 1987).

Better understanding of global change requires a broad view of the range of options available for choice, and knowledge of the likely efficacy of alternative options for managing the long-term, large-scale interactions between human and environmental systems.

### Perceptions

Finally, choices are based on people's perceptions and assessments of how the world system works, how and why it is changing, how its changes are connected to things they value, and how choices among options for action can alter those connections.

In contexts as complex as global change, perceptions and assessments will inevitably differ from reality for reasons of fundamental ignorance or uncertainty—i.e., the actual causes and effects of change are not understood by anyone. Such fundamental inaccuracies increase as one moves along the chain of causation from outcomes cast in terms of altered material and energy flows in the physical environment, to ecosystem-level impacts of such alterations, to consequences for individuals and entire social systems (Schneider, 1983). These difficulties are only partially overcome by the wide array of formal assessment methods that have been developed over the last two decades.<sup>7</sup>

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<sup>7</sup> Examples include technology assessment (Shrader-Frechette, 1985), environmental impact assessment (e.g., Bisset, 1987; Munn, 1979), risk assessment (e.g., Covello et al., 1985; Whyte and Burton, 1980), and efforts to provide more comprehensive social impact assessments (e.g., Kates et al., 1985; Leistritz and Ekstrom, 1986; McAllister, 1982).

Inadequate education and poor communication of expert assessments limit the accuracy of perceptions on which choices are based. But experience suggests a wide range of other potentially limiting factors that are characteristic of the choosers themselves rather than the experts. These may include the proximity of an individual to environmental damage; exposure to mass media, education, variety of life experience, age, cultural and organizational context, and a number of other issues (Douglas and Wildavsky, 1982; Tang and Jacobson, 1988). Explaining and predicting interactions between human and environmental systems require understanding of different peoples' perceptions of global change and their roles in it, the factors that cause variation or distortion in those perceptions, and the steps that can be taken to make formal assessments more accurate and useful.

### Culture

Human interactions with the global environment, as well as human choices regarding environmental management, are ultimately grounded in a wealth of underlying social factors and historical contexts that might be called "culture." Patterns of global environmental change can be described without reference to cultural factors. But because of the integral role of human systems in the dynamics of global change, some understanding of why societies function as they do will be required for explaining and predicting interactions between people and their environments.

A long-standing debate exists on the relative importance of various cultural factors as causes of environmental change and as determinants of the consequences that such changes have for people (e.g., Garcia, 1981). That debate is sure to intensify with increased attention to the problems of global change. In fact, however, the practical difficulty is not to imagine ways in which cultural variation might influence global change. Rather, it is to bound the consideration of contributing cultural factors in a way that leads to efficient explanations, and thus keeps research on the human component of global change from becoming synonymous with research on social systems in general.<sup>8</sup> It thus seems prudent to focus initial global change studies on the dimensions of culture that existing scholarship

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<sup>8</sup> An analogous case was successfully argued early in the evolution of the natural science components of the IGBP. As a result, the natural science component of IGBP does *not* involve most environmental science, but rather focuses on the small but important

indicates are almost certainly central to the long-term, large-scale interactions of human and environmental systems. These include the structure, distribution, and growth of human populations, the modes of social, political, and economic organization adopted by those populations, and the resulting state of agricultural, industrial, and general economic development. (The cultural dimensions of environmental values and attitudes are also sure to be important, as noted earlier.)

### Population<sup>9</sup>

Population characteristics are clearly among the most fundamental human dimensions of global change, with direct implications for resource use, waste production, and social vulnerability (Repetto, 1987). Despite continuing declines in fertility rates throughout much of the world, the human population of the earth is almost certain to more than double within the next century. Migration-induced changes in the distribution of population are even more dramatic than population growth *per se*. Fifty years ago, less than one quarter of the world's population lived in urban areas; fifty years from now, more than half will (United Nations, 1985a,b). Moreover, trends toward very large cities will almost certainly entail nonlinear implications for human interactions with the environment (Baochang et al., in press). Despite years of discussion on the interactions of population, resources, and environment, however, there is still only limited understanding of how the elements of long-term, large-scale human population dynamics (e.g., fertility, migration, age distribution, and life expectancy) affect either sources of environmental change or the implications of those changes for people.<sup>10</sup>

### Organization

A second set of underlying human dimensions of global change can be grouped under the heading of social institutions or organizations. In the broadly defined sense employed here, "organization"

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subset of science necessary to explain certain long-term, global, interactive environmental changes.

<sup>9</sup>This section draws heavily on the report of the U.S.-China Workshop on the Human Dimensions of Global Change (Tang and Hacobson, 1988).

<sup>10</sup>See, for example, the materials of the Population, Resources and Environment Program (PREP) of the American Association for the Advancement of Science (AAAS).

includes such forms of human interaction as the family, markets, corporations, command and regulatory aspects of government, voluntary associations, religious structures, laws, education, the media, and variety of international arrangements. The mix and strength of such mechanisms clearly vary around the world, and it would be surprising indeed if this variation did not have implications for the interactions between people and their environments. We know little about the environmental implications of the different organizational means of seeking human well-being. We do not know much more about what determines the efficacy of alternative organizational approaches to incorporating environmental considerations in the social calculus (Tang and Jacobson, 1988). Clearly, the nation state is one of the most important organizational structures involved in determining the interaction of human and environmental systems. But underlying structures determining local property rights and access to resources also have a substantial impact on what people actually do to their environments, and should not be overlooked (Hägerstrand, 1988).

Perhaps the most significant organizational trend for studies of global change is the worldwide growth in the reach and power of human institutions that has been gathering momentum over the last several hundred years, and seems likely to accelerate into the future. Most organizational forms, over most of their history, have been preoccupied with more or less immediate goals of physical, economic, and spiritual security. It is only relatively recently that a few organizational structures have emerged with self-professed goals of environmental protection and environmentally sustainable development (Richards, 1986). Especially needed is a deeper understanding of those emerging organizations with global reach and those capable of forcing particularly rapid change in human interactions with the environment.

### Development

As important as population growth, structure, and distribution may be, they represent only the ultimate foundations on which rest the human activities that are the proximate sources and receivers of global change. Trends in resource use per capita must be considered along with trends in population density per se if we are to understand variations in total pressures on the environment exerted by different societies around the world (Clark, 1986; Goldemberg et al.,

1987). Similarly, the character of a region's resource use, productive activities, and trade relations is an important determinant of its vulnerability to environmental change (Burton et al., 1978; Chisholm, 1982; Parry et al., 1988). In general, efforts to understand the underlying cultural dimensions of global environmental change must also look to long-term, large-scale changes in how people produce and consume goods and services. Industrial and agricultural processes have for centuries been the human activities with the greatest consequences for environmental change. In the latter part of the present century, energy-related activities have also become important developmental dimensions of global change (Clark, 1986; Turner et al., in press). For example, prior to 1950 the majority of carbon dioxide released to the atmosphere through human activities came from biomass burning. Since that time the majority has come from fossil fuel combustion (Bolin, 1986). Consumptive end use processes are also increasingly evident as major agents of global change (Ayres and Rod, 1986).

Two basic issues arise in efforts to understand the past and future role of major development trends in global change. The first concerns the concept of "sustainability," defined by the Brundtland Commission as the capacity to provide for the needs of the present without diminishing the options of future generations (WCED, 1987).<sup>11</sup> Despite the importance and popularity of the sustainability theme, there is still little understanding of just what constitutes a sustainable, as opposed to an unsustainable, development path. Needed are not only more careful case histories of how environmental change has influenced development, but also a framework of concepts and causal hypotheses for use in synthesizing and generalizing the cases.<sup>12</sup>

A second and related developmental dimension of global change concerns alternative paths or models of development per se. What feasible and desirable paths would reflect a more balanced view of physical, economic, and environmental well-being or security than has traditionally been the case? What international processes would best catalyze and legitimize the search for such alternatives? What suite of development indicators would eliminate the worst imbalances and biases of current measures, and provide more meaningful and

<sup>11</sup>For a review of alternative definitions and their problems, see B. J. Brown et al. (1987).

<sup>12</sup>Some of the issues, initiatives, and difficulties are set forth in Clark and Munn (1986), Jacobs and Monroe (1987), and Liverman et al. (1988).

useful documentation of progress toward the sustainable development of the earth?<sup>13</sup>

### UNRESOLVED QUESTIONS

The previous section identified the human elements involved in long-term, large-scale interactions with the environment. This section outlines some of the most important questions regarding those interacting elements that need to be resolved in order to better explain, predict, and manage global change. In preparing this discussion, an effort has been made to summarize and critically evaluate the main conclusions of the numerous recent workshops, symposia, and writings on the human dimensions of global change that were noted at the beginning of this paper. The results are presented below under three related headings: human sources, human consequences, and human management of global change.

#### Human Sources of Global Change

An early target of research on global change should be documentation and understanding of the most important ways in which human processes drive or force changes in the environmental system. Experience with study of the greenhouse problem and stratospheric ozone depletion shows that accurate histories of emissions resulting from human processes are necessary to differentiate among competing theories or models of global change. The same experience shows that using superficial trend-extrapolation scenarios of future emissions resulting from human processes can seriously misdirect the attention of the research community. Finally, more informed social choices regarding environmental management require better understanding of not only how, but also why, the human forcing of global change varies with time, space, and culture. Such understanding will require better answers to the three related groups of questions discussed below.

<sup>13</sup>The problem of developing more useful indicators of sustainable development is beginning to be addressed in a number of efforts. For a sample of current work, see Liverman et al. (1988), IIED/WRI (1987), and Daly (1988). The long and not altogether happy history of work on social indicators is relevant to this effort. For a broad perspective on the social indicators work, see SSRC (1983) and Ferriss (1988).

### Identifying Human Activities That Drive Global Change

Which anthropogenic alterations to material and energy flows within the geosphere-biosphere system play significant roles in forcing global change? Which human processes are significant sources of such alterations? How do answers to these questions vary across space, time, and culture?

The first requirement is for a more systematic identification of which human-induced changes in energy and chemical flows, water use, habitat extent, or other variables constitute the most significant "inputs" to climatic, biogeochemical, or biotic dynamics. For a few aspects of global change like the greenhouse effect or stratospheric ozone depletion, this preliminary identification of "input" linkages between the human and other components of global change is relatively well in hand: research can confidently focus on a specific list of radiatively active trace gases and halocarbons. For most other aspects of global change, however, much basic research on human forcing of interactions with the environment needs to be done.

Figure 3 gives a simple conceptual framework for the process of explicitly and systematically identifying the important linkages among components of the geosphere-biosphere system. The entries in the "human component" cell of the figure are drawn from NASA's Earth System Science Committee report *Earth System Science: A Closer View*, one of the most recent and most systematic efforts to set priorities for linkage information.<sup>14</sup> Those entries are nonetheless preliminary and incomplete, reflecting only partial reviews of the knowledge about human activities that researchers working on the natural components of global change believe they need in order to test their models and make predictions. Moreover, to be maximally useful, such priority lists of potential anthropogenic forcing functions must also specify the scale, resolution, and accuracy required of the input data if they are to be useful in advancing overall understanding of global change. Needed as well is information on the threshold rates or quantities above which specified anthropogenic inputs, although not now of great concern, would become potentially important agents of global change.

Despite these demanding requirements, however, the kind of perspective suggested in Figure 3 needs to be developed systematically

<sup>14</sup>Earth System Science Committee (1988): Figure 2.4.2. Note that an earlier and more detailed effort, though restricted to a single component of the geosphere-biosphere system, is available in the NRC (1994) report *Global Tropospheric Chemistry*.



Needed By Needed from		Human Component	Biotic Component	Biogeochemical Component	Climatic Component
Human Component		(Internal social dynamics) • Changes in major ecological zone boundaries • Changes in productivity potential	• Land use transforms • Yield management ?	• Land use transforms • $\phi$ CO <sub>2</sub> , NO <sub>x</sub> , SO <sub>x</sub> ?	• Land use transforms • $\phi$ greenhouse gas • $\phi$ aerosols • Albedo change • Water distribution
Biotic Component			(Internal biotic dynamics)	?	?
Biogeochemical Component		• "air quality" • "water quality" • $\phi$ toxics in soil	?	(Internal biogeochemical dynamics)	?
Climatic Component		• regional temp. statistics • regional ppt statistics • regional ice statistics	?	?	(Internal climatic dynamics)

FIGURE 3 A framework for defining linkages among components of the geosphere-biosphere system. In the "looking outward" or systems approach of this framework, attention is focused on what studies of each component need to know from other components in order to proceed with their work (Holling, 1978). The entries in the cells of the figure are illustrative only, reflecting the needs from and by human component studies as defined in NASA's ESSC (1988). Note that " $\phi$ " indicates fluxes.

as a useful first step in setting priority targets for studies on the energy flows, chemicals, habitats, water flows, physical properties, and biological entities that constitute the most important links between human activities and rest of the geosphere-biosphere system. Initial efforts will doubtless guess wrongly on some of the important connections. But only by making such guesses explicit, and testing whether models incorporating them in fact have predictive value, can cumulative progress in the understanding of global change per se be expected.

Once a priority list of linkage variables has been defined, there remains the question of which specific human activities are capable of changing the fluxes of those variables. Even in relatively simple cases, this analysis is not trivial (e.g., Wuebbles and Edmonds, 1988). Establishing the required knowledge base will require close collaboration between scientists studying the relevant nonhuman components of global change and specialists in the workings of relevant technologies and land use practices (especially chemical, water, mechanical, and agricultural engineers). Figure 4, drawn from one such collaborative effort, suggests the wide range of human processes that force changes in just a few of the chemical species of importance to global change. Again, the further development of such frameworks of interactions is a crucial early step in research to understand the interactions between human and environmental components of global change.

#### Input-Output Relationships in Human Activities

How much alteration of the relevant material or energy flows is created per unit of human source activity? How do these "intensive" relationships between human processes and material and energy flows vary across space, time, and culture?

Answering these questions will require basic quantitative process studies on the transformation of human activity "inputs" such as coke production or rice paddy cultivation into "outputs" such as methane flux to the atmosphere. Engineering expertise will again be essential to the task. Typical of the most complete work on individual inputs and outputs is the work on quantities of carbon dioxide produced per unit energy derived from various fossil fuels (Marland and Rotty, 1983). Even in the carbon dioxide case, however, comparable input/output (I/O) coefficients for various types of land use conversion activities are still underdeveloped.

EMISSION SOURCE	ENVIRONMENTAL COMPONENT						
	NOx	SOx	HCl	Sea Salt	CH4	CO	N2O
PRODUCTION/DISTRIBUTION OF MINERAL FUELS							
Coal					X		
Oil					X		
Natural Gas					X		
COMBUSTION OF MINERAL FUELS							
Coal	X	X	X			X	X
Oil	X	X	X				X
Gasoline						X	
Other						X	
Natural Gas	X	X	X				X
INDUSTRIAL PROCESSES							
Coke Production					X		
Pig Iron Production						X	
Smelting of							
Copper		X					
Lead		X					
Zinc		X					
AGRICULTURAL							
Biomass Combustion	X				X	X	X
Nitrogen Fertilizers	X						X
Rice Paddy Cultivation					X		
Ruminant Animal Grazing					X		
MISCELLANEOUS							
Industrial uses, refrigerants, consumer products							
Landfills					X		
Oceans				X			
Wetlands					X		

FIGURE 4 Human processes that force changes in selected chemical constituents of the atmospheric environment. These illustrative data are drawn from a study by Darnstadter et al. (1987, Vol. 2: B3).

The relative simplicity of the I/O structure for the case of carbon dioxide emissions is potentially misleading as a guide to research requirements in this complex area. In the more general situation suggested in Figure 4, a given pollutant flow will be altered through several human activities. Complex sequences of reaction, deposition, and remobilization may be involved within the human system en route to a final measured "output" into the environment. At each stage, process understanding is usually imperfect, as is monitoring data for estimating fluxes and pools. An important methodological advance in dealing with such complexities in I/O assessments has therefore been "materials/energy balance accounting" (Ayres, 1978). This approach takes advantage of conservation principles to balance amounts of energy and materials drawn into the human system with

amounts exported or stored at any given time. It focuses attention on the fact that all energy and materials used in human development have to go somewhere, even when monitoring data fail to find them. It has helped in the "discovery" of unsuspected pollutant sources in seemingly innocuous or irrelevant human activities (Ayres and Rod, 1986). More systematic use of balance accounting would almost certainly be useful in future efforts to answer questions concerning the I/O relations between human and other components of the geosphere-biosphere system.

An especially difficult but necessary aspect of I/O studies will be their historical dimension. Long-term changes in the completeness of combustion or depth of plowing may be more important for certain environmental emissions than changes in the total amount of combustion or extent of arable land. Ignoring historical changes in the I/O relations can lead to serious errors in understanding the human role in global change. For example, the uncritical use of contemporary emission coefficients for assessment of historical carbon monoxide emissions in the United States has almost certainly resulted in cumulative estimates that are significantly too low (Darmstadter et al., 1987: App. A:26). Table 1 shows the kinds of results that careful collaborative research can produce. Much more research is needed, however, to produce comprehensive assessments of the I/O coefficients required to characterize the full set of interactions suggested above.

#### The Changing Magnitude of Human Forcing

What are the total amounts or strengths of the relevant human source activities? How do these "extensive" measures of the human dimension of global change vary across space, time, and culture? Ultimately, the need is for something approaching a theory of world development, cast in terms appropriate to produce relevant human forcing functions needed for the understanding of global environmental change. The underlying research questions were summarized in a recent Social Science Research Council (SSRC) meeting on changes in the global environment:

What are the persistent, broad-scale social structures and processes that underlie these changes? In particular, what are the relative roles of the amount and concentration of human population, the character and use of technology, the changing relation between places of production and consumption, and the "reach" and power of state and other institutional structures? How does

TABLE 1 Reconstruction of Historical Methane Emission Coefficients, Reflecting Changes in Human Economy and Technology

	Methane Emissions Coefficients (metric tons CH <sub>4</sub> /metric ton of fuel)					
	1800	1860	1890	1920	1950	1980
Anthracite	--	0.005	0.006	0.007	0.007	0.007
Appalachian bituminous (underground)	0.005	0.005	0.005	0.005	0.005	0.005
U.S. Average bituminous	--	--	0.005	0.005	0.005	0.005
Coking (based on coal used for coking)	--	--	0.27	0.054	0.03	--
Gas (based on unaccounted potential production of associated gas)	--	.30	.25	.22	.20	--
Gas distribution (based on gas marketed)	--	--	.03	-0.02	0.01	0.01

NOTE: This example is drawn from the study by Darmstadter et al. (1987, Vol. 2: A83) on the impact of world development on the atmosphere. The listed coefficients are expressed as tons of CH<sub>4</sub>/ton of fuel. Dashes reflect missing data.

the relative importance of these roles for environmental change vary across cultures, and through history? (Social Science Research Council, 1988)

Among the earliest efforts to address such questions at the global scale were the various world systems modeling efforts of the 1970s (e.g., CEQ, 1980; Meadows et al., 1972). The shortcomings of these efforts are well known and can be traced to weaknesses in data, methodology, and conceptual foundations (Brewer, 1986; Greenberger et al., 1983; Meadows and Robinson, 1985; Office of Technology Assessment, 1982). A number of more modest efforts, focused on particular sectors of the human system, have since been carried out. Several of these, specifically in the fields of population, agriculture, forestry, and energy modeling, are relevant to studies of global change.<sup>15</sup> As pointed out in a recent review by the International

<sup>15</sup>Representative of the best work is United Nations (1985b) on population, U.N.

Institute for Applied Systems Analysis, however, the assumptions underlying the best of these sectoral studies are often contradictory in ways that can only partially be resolved through subsequent re-analysis (Toth et al., 1988). No credible integrated and dynamic model yet exists of long-term global changes in human activities that force environmental change. Prospects for such a model, while still distant, are nonetheless improving and need to be pursued as part of a research program on global change. As regards data, many of the most important contemporary human releases of materials and energy relevant to global change are monitored through national and international environmental networks. A careful review is needed, however, of the adequacy of this contemporary monitoring for the specific purposes of global change research. On the methodological side, another recent SSRC study has illustrated how much the social and natural sciences can learn from each other as they struggle with their parallel problems of modeling and predicting global change (Land and Schneider, 1987). Finally, initial attempts to provide conceptual foundations for long-term global studies of human development can be seen in historians' debates on "the modern world system" and investigations of "long-wave" phenomena in economic life (Braudel, 1984; Vasko, 1987; Wallerstein, 1974). Although most of this work has ignored environmental and resource dimensions of the world system, some impressive recent efforts of geographers and historians are beginning to formulate a theory of global human ecology as such (Chisholm, 1982; Richards, 1986; Turner et al., in press). This work needs to be pursued in close collaboration with other global change studies if we are to better understand the changing magnitude of human forcing activities.

### **Human Consequences of Global Change**

The complex processes involved in human responses to global change were outlined above in the section on principal elements. As summarized by the 1987 Ann Arbor Workshop on an "International Social Science Research Program on Global Change":

Human beings can respond to global change in a variety of ways, ranging from accepting change and adapting to it, to attempting

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Food and Agriculture Organization (1981) for agriculture, Kallio et al. (1987) for forestry, and Edmonds and Reilly (1985) and Nordhaus and Hohe (1983) for energy. An overview of other global sectoral forecasts relevant to global change is given in Toth et al. (1988).

to limit change by modifying their behavior. The human response depends first on cognitive processes, on perceiving change and its consequences, and then on the possibilities that human beings see for affecting change and the values that they hold. (Jacobson and Shanks, 1987:21)

Formal assessments of global change and its consequences aim to help make human perceptions more useful and effective guides to action. Research to improve assessments is therefore central to an improved understanding of the interactions between human and environmental systems. Summarized below are the principal questions regarding assessment that should be addressed in the early stages of a research program on the human dimensions of global change. Questions relating to management or the "possibilities for affecting change" referred to above are dealt with in a later section on management.

#### Determining the Environmental Dimensions of Human Vulnerability

As noted earlier, notions of social vulnerability are central to advancing the understanding of human responses to global change. A basic research task is thus to identify what kinds of change, and what rates of change, are those to which people in different cultural settings are most vulnerable. More precisely, what information concerning the character, timing, and location of possible changes in the earth's biogeochemical, climatic, hydrologic, and biotic processes is needed as inputs to studies attempting to understand and expand the boundaries of sustainable development?<sup>16</sup>

The conceptual framework required for addressing this question is thus the same as that introduced earlier in Figure 3. In this case, however, knowledge of the human system's sensitivities rather than the environmental system's sensitivities must provide the point of departure. Without explicit guidance from scholars of human development regarding the kind, scale, and resolution of information needed to assess important aspects of social vulnerability to environmental change, natural scientists cannot be expected to focus on the few aspects of change that are most important to people (Chen and Parry, 1988).

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<sup>16</sup> A strong case for such management-driven definitions of data needs is made for the case of studies on climate warming in Jaeger (1988).

How might scholars of human response best advance their task of articulating priority needs for specific kinds of information about global environmental change? Useful approaches are suggested by existing work in the study of natural hazards, climate change, and the environmental effects of nuclear war (Burton et al., 1978; Harwell and Hutchinson, 1985; Kates et al., 1985). A particularly instructive approach has been applied by Dr. Martin Parry to address the response of sensitive agricultural systems to climatic variation and change (Parry et al., 1988). This begins by focusing on agricultural regions that are on the margin of economic viability with respect to temperature or moisture conditions. Rather than asking how these systems would respond to climate change in general, it then analyzes the social, economic, and agronomic characteristics of each region to assess the limits of climate change beyond which significant disruption or displacement of agricultural activity would be expected to occur. The challenge is then thrown back to the climatologists to estimate whether, and when, changes of such magnitude might be expected due to natural variability or anthropogenic forcing.

Efforts are now needed to move beyond climatic considerations in asking what kinds of environmental change are most important for people. An excellent foundation for this task is provided by the recently published proceedings of the Dahlem Conference on *World Resources and Development* (McLaren and Skinner, 1987). This mammoth work brings together some of the best social and natural science thinking on specific interactions among environmental change, resource availability, and sustainable development. It could be profitably tapped in an early effort to identify the specific aspects of global environmental change to which various societies, sectors, and populations are most vulnerable.

#### Assessing Syndromes of Environmental Transformation

Multidimensional "syndromes" of environmental transformation are a central feature of global change (Regier and Baskerville, 1986). For example, the sustainability of forest resource use in some regions is simultaneously threatened by changes in land allocation, climate, and atmospheric chemistry. The resulting syndrome of forest resource degradation is the environmental change that must ultimately be explained and the policy problem that must ultimately be addressed. Other syndromes of environmental change, such as those associated with development of the rich and diverse farming



landscapes of Normandy, can be viewed as positive transformations. In general, however, assessments must move beyond problem-by-problem formulations to provide a synoptic or integrated account of the overall environmental changes and consequences that result from specific patterns or strategies of human development.

To date, however, most of the relatively few assessments that have addressed large-scale environmental changes have dealt with the relationships between single environmental components, e.g., acid deposition, and single development sectors, e.g., forestry. Even the most ambitious works, for example, the National Research Council's and the Organization for Economic Cooperation and Development's programs on environmental impacts of energy production, or the Scientific Committee on Problems of the Environment's program on climate impact assessment, have dealt only with the impacts of change in a single valued environmental component across a range of human activities, or the impacts of a single human activity across a range of valued environmental components (Brooks and Hollander, 1979; Kates et al., 1985; Torrens, 1984). The assessment of multiple threats or, more generally, change syndromes per se has been largely ignored.

One notable exception to this situation is provided by the experiments in syndrome assessment conducted in recent years by Thomas Graedel of AT&T Bell Laboratories and Paul Crutzen of the Max-Planck Institute (Crutzen and Graedel, 1986; Darmstadter et al., 1987). A sample of their work, dealing with valued components of the atmospheric environment, is reproduced in Figure 5. The relative simplicity of the figure should not be allowed to disguise either the tremendous amount of research necessary to provide the findings it portrays, nor the incomplete nature of the results obtained. Shortcomings of current results, as pointed out by the authors, include questions of scope, the failure to include assessment of impacts on people as well as environment per se, and difficulties of making explicit the subjective judgments that such synoptic work inevitably entails. But it would be hard to overestimate the importance of continuing experiments to produce, in readily communicable forms, synoptic and dynamic assessments of our inevitably incomplete knowledge about the syndromes of global environmental change.

### Linking Spatial Scales in Assessments of Global Change

A central question that needs to be answered for better assessments is how to link global change to local conditions at intermediate or regional scales. Much of what is interesting or worrisome in global change seems to consist of people in one set of places taking actions that have their major consequences for other people in other places.<sup>17</sup> Much of sustainability relates to importing needs or exporting wastes from one place to another. Finally, the values, options, and perceptions central to human choices regarding global change differ widely from place to place on earth. The uniqueness of and interactions among places are thus central to the human meaning of global change and to the prospects for managing sustainable development. Yet they are poorly captured (if addressed at all) by current assessment practices. Only the barest outlines of an approach to improve this situation have been sketched (Chisholm, 1980; Clark, 1987). At least two related research tasks nonetheless merit early attention.
























*Mapping Vulnerabilities.* Work in the assessment of climate impacts has demonstrated the utility of focusing on places and peoples that are especially vulnerable or sensitive to specific kinds of climatic change and variation (Parry, 1985). The search for regions and social groups that are especially vulnerable to global change should now be extended to include consideration of other environmental components. For example, we could and should know more than we do about which human societies would be most seriously at risk under scenarios of continued depletion of stratospheric ozone.

Even more important, and even more difficult, is the task of identifying places and peoples that are likely to be particularly vulnerable to the "syndromes" of multiple environmental changes discussed earlier. Boundaries of the geographic regions or social groupings most threatened by each individual component of environmental change will in general not be entirely congruent. It will therefore be necessary to search for situations where especially worrisome changes in several valued environmental components overlap at particular locations. The concepts and tools of geographic information systems

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<sup>17</sup>As John Firor (National Center for Atmospheric Research) put it in commenting on an earlier version of this draft: "How do we deal with the possibility that burning fuel in Japan may flood Bangladesh, or cutting trees in Brazil may impact forest migrations in Kentucky?" (Letter to William Clark, April 15, 1988).

Valued Environmental Components

Sources of Change	Strato- spheric Ozone Change	Global Radia- tion Balance	Oxi- dant	Acidic Precip- itation	Visi- bility	Corro- sion	Impact
Oceans, Estuaries							4
Natural Vegetation							3
Animals							2
Biomass Burning							7
Crop Production							5
Fossil Fuel Combustion							19
Industrial Processes							13

Sources of Change

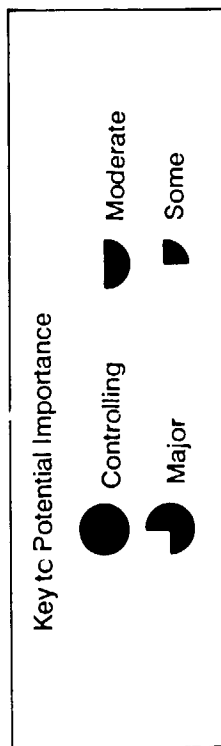


FIGURE 5 Assessing syndromes of environmental change. An example of the required integrated assessment perspective is suggested in this figure, developed to show the overall consequences for the atmospheric environment of changes in a wide range of human and natural processes (Crutzen and Graedel, 1986). Each cell of the matrix reflects one of the classical single-cause, single-consequence assessments. Although there is no mechanistic way that cell values can be quantitatively combined, each "column total" would in principle represent the net effect of all sources of change on a single environmental component. Each "row total" would indicate the net effect of a single source of change on a wide range of environmental components. (Significantly, these "row totals" are equivalent to the integrated sectoral perspective on sustainable human activities and global change recently advanced by the U.N.'s Brundtland Commission on Environment and Development.) The matrix as a whole constitutes a qualitative synopsis of global (atmospheric) change.

seem especially well suited to the required mapping task. A useful guide to what will be required of research on this topic is provided by contemporary efforts to map areas with a high risk of forest mortality under multiple stresses of acid deposition, tropospheric oxidants, drought, and other factors (UNECE, 1983). More broadly, efforts should be undertaken to examine previous episodes of rapid regional environmental change to identify the determinants of vulnerability.

*Global Linkages in the Assessment of Social Vulnerability.* While a regional focus for assessments will be essential to understanding the human meaning of global change, it is equally essential that the global linkages among regions not be ignored. It was recognized some time ago, for example, that the social significance of a prolonged drought in the North American grain belt would depend strongly on what was happening to the weather in other major grain growing regions of the world. Nonetheless, most contemporary assessments of global climate change still manage only to tally consequences for a selection of regions considered independently, as though they were on different planets.<sup>18</sup> Related shortcomings characterize the country-by-country approach to recent assessments of forest damage in Europe (Nilsson and Duinker, 1987).

Conceptual and methodological improvements in approaches to assessing the human implications of linkages among regional consequences of global change are badly needed. They will require close collaboration between natural scientists concerned with global patterns of environmental change (e.g., the "teleconnections" of climatology) and social scientists concerned with the economic, political, and other human processes around the world. Preliminary studies seeking to address the linkage issue suggest that global models of resource and commodity trade are likely to be a necessary component of such assessments (e.g., Binkley, 1988; Williams et al., 1988). Substantial use of explicit scenarios of environmental change and human development will also be required (Brewer, 1986).

#### Incorporating Values in Assessments of Global Change

The values that figure so prominently in the determination of

<sup>18</sup>Stewart and Glantz (1985) have pointed out this difficulty in the ostensibly global climate impact assessment by the National Defense University. The problem persists even in the most recent work, however—e.g., the Villach/Bellagio review of policies for dealing with climatic change (Jaeger, 1988).

human choice are not adequately reflected in most environmental assessments. The special problems raised by global environmental change—among them multigeneration time horizons, multinational spatial scales, and the prospect of irreversibility—increase both the difficulties and the importance of doing better. Research in environmental economics has made some progress in addressing the value issues that arise in the treatment of externalities and the valuation of nonmarket goods. The field has nonetheless found it extremely difficult to provide a balanced treatment of values other than efficiency in its assessment calculus (Kneese and Schulze, 1985). Other disciplines, including those concerned with legal and ethical issues, have begun to address some of the key issues of equity and multigenerational tradeoffs in a global change context (e.g., Brown-Weiss, 1984, 1988). Progress has nonetheless been slow. A concerted, multidisciplinary attack on these questions should be given high priority in research on the human dimensions of global change. At least two other issues, however, merit equally serious attention.

*Valued Environmental Components.* As noted earlier, experience in environmental impact assessment emphasizes the importance of focusing assessments on a relatively few “valued environmental components” like summer soil moisture or tropical species diversity (Beanlands and Duinker, 1983). The list of components is always subject to revision, but efforts to include everything simply devalue everything. Scientists have an important input to make to the selection of valued environmental components for research programs on global change, but so do the policymakers who will be asked to use the results and the public who will be asked to pay the bills. Procedures need to be designed that will help different groups affected by global change to identify and articulate the components they value most. Special attention is needed on how to give fair consideration to the values of traditionally underrepresented groups—the poor, the uneducated, the unborn. Also needed are fora and negotiating processes that can promote agreement among groups on the core valued environmental components to be addressed in mutually supported programs of global change research. A variety of workshop methods have evolved over the last decade to facilitate such negotiations for small-scale environmental problems. But these approaches must still be evaluated and adapted to the context of long-term, global interactions between human and environmental systems (Sonntag, 1986).

*Attitudes Toward Risk and Uncertainty.* People's inevitably incomplete understanding of global change means that all assessments are bound to be riddled with uncertainties. This raises a number of important value-related questions that should be addressed in research programs on the human dimensions of global change. For example, studies of human attitudes toward risk have shown that different individuals or organizations confronting the same objective uncertainties will place significantly different values on actions to remove the uncertainty or avoid its possible consequences. Put oversimply, some people will be more risk averse than others; these differences will have significant implications for the choices societies make when confronted with environmental threats (Fischhoff et al., 1981; Kleindorfer and Kunreuther, 1986). Moreover, we know that the form in which risks are communicated to people can make a tremendous difference in their resulting behavior. Most research, however, has focused on perceptions of environmental risks very different from those posed by global change. We know very little, for example, about how people evaluate highly uncertain predictions of high-consequence, large-scale, relatively irreversible events.<sup>19</sup> Better understanding is needed of how such values can be measured, how they vary with space and time, and how they can be incorporated in assessments of global change. The implications of ways in which such assessments are communicated through technical and mass media also need study. Even more fundamentally, it will be important to follow up the leads of anthropological research that suggest how cultural factors shape the ways in which people and organizations value uncertain environmental risks (Douglas, 1966, 1986; Douglas and Wildavsky, 1982).

### Human Management of Global Change

A major challenge of coming decades is to learn how long-term, broad-scale interactions between human activities and the earth's environment can be managed to increase the prospects for sustainable improvements in people's well-being. Management is not the same as prediction or even understanding. The distinction is an important one, for management can be improved despite the enormous uncertainties and downright ignorance that will continue to make detailed

<sup>19</sup> For some initial findings in a rigorous comparative perspective, see Kates et al. (1985).

predictions illusory. A central question is whether we are in fact improving our management of environmental change, and, if so, which forms of social action are most effective in what situations (White, 1988a). Improvements in the management of global change can be defined in terms of their ability to increase social choice and decrease vulnerability in the face of uncertain futures of both environmental change and human objectives.<sup>20</sup>

Which management options should be *adopted* in the face of global change is a matter for resolution through the policy process. But increasing the range of management options, and characterizing their likely performance, should be a central focus for invention, imagination, and research applied to the human component of global change. The basic research challenge was set forth by the Ann Arbor workshop on an International Social Science Research Program on Global Change as follows:

Human societies have at least some capacity to act on perceptions, to diminish the rate or even alter the course of their environmentally destructive activities. Too little is known, however, about the actual strength and limits of these adaptive capacities. Perception is one thing, changing entrenched patterns of need-gratifying behavior is quite another. It seems both possible and essential, therefore, to encourage intensive study of the response mechanisms that may mitigate, or fail to mitigate, environmentally threatening human activities. (Jacobson and Shanks, 1987:26ff)

In the broad sense used here, efforts to manage global change involve changes in technologies, institutions, or behavior of individuals. No serious effort has yet assessed the relative efficacy of efforts to employ these three mechanisms for managing environmental change. Such an examination is especially important for a global change program because of the rapid increases in scale of the environmental transformations that must be managed. It is not clear that there is much precedent for dealing with the long-term, broad-scale issues that are increasingly at the forefront of concern.<sup>21</sup>

<sup>20</sup>The preceding paragraph is a paraphrase from the planning documents of the International Institute of Applied Systems Analysis's biosphere program as published in Clark (1986).

<sup>21</sup>Partial exceptions worth examining for what they have to say about contemporary concerns for global change are the limited test ban treaty for nuclear weapons, the law of the sea, and the international ozone protocol. For perspective, see McLaren and Skinner (1987) and Kay and Jacobson (1983).



### Technology and the Management of Global Change

Technical change is rapidly accelerating, mostly in pursuit of objectives that have little direct connection with environment. On the scale of years, technological innovations can be expected to make only a limited difference in the management of global change.<sup>22</sup> On a scale of decades, however, the consequences—intended and incidental—of technological change for environmental change can be tremendous. Work on life-cycle dynamics of major technical processes suggests that 20 to 40 years is sufficient for oil to displace coal as a world energy source, for the steel industry to shift from open hearth to electric arc processing, or for world turpentine production to shift from biotic to chemical feedstocks (Clark, 1987). Each of these developments, and many others like them, have had major implications for environmental change, though few were undertaken with environmental issues in mind. Turning to intentional use of technology to manage environmental change, options exist to eliminate atmospheric emissions of sulfur dioxide and carbon dioxide due to fossil fuel production (e.g., Haefele et al., 1986) and to radically reduce the danger posed by halocarbons to stratospheric ozone. But between these observations of technical feasibility and useful assessment of the management options that technologies might offer for dealing with global change are a number of basic research questions that have been only partially addressed by existing studies:

- What are the major technological trends that are likely to restructure the nature of interactions between environment and development over the next several decades?
- What technological opportunities appear most promising in light of what we understand about the quantities and qualities of the key flows of materials and energy involved in global change (White et al., 1988)?
- What are the necessary conditions to induce technical innovations that would relax the constraints posed by global change (Runge, 1986)?
- What are realistic penetration and diffusion times for such innovations in the world market (Pry, 1973)?

<sup>22</sup>The role played by the development of substitutes for certain chlorofluorocarbons in the promotion of the Montreal Protocol on the Ozone Layer may be, but probably is not, something of an exception. See Office of Technology Assessment (1988).

- How can both innovation and diffusion of technologies supportive of sustainable development be encouraged in an increasingly internationalized technology market (Guile and Brooks, 1987)?
- To what extent will it be most productive to pose the above questions not for individual technologies, but rather for groups of tightly interacting and therefore "co-evolving" technologies (R. Chen, personal communication)?

### Institutions and the Management of Global Change

Humans organize their responses to global change through a wide range of institutions and other structures. The fundamental research challenge is to understand the relative effectiveness of alternative institutions as mechanisms for management of interactions between human and environmental systems. The institutions to be examined include not only those involved in classic market and national regulatory functions, but also an increasing array of voluntary and international organizations. All of these structures, plus the bodies of policy, law, and practice they reflect, are evolving rapidly in terms of reach and power. Each country's management options are increasingly influenced and constrained by the institutions and policies of other countries. A dynamic, global perspective on the changing efficacy of alternative institutions for managing global change is therefore necessary, backed by appropriate comparative and historical research. A limited body of existing scholarship on national and international mechanisms for managing large-scale environmental change provides the foundations on which such research can build (e.g., Caldwell, 1984; Carroll, 1983; Kay and Jacobson, 1983). Among the specific questions to emerge from recent reviews, the following stand out as meriting high-priority attention:

- What is the special place of the nation-state in managing the interactions between human and environmental systems? How are economy/environment interactions treated in national policy processes? What determines the prospects for interstate cooperation on environmental problems? How do domestic interests reflect on such foreign policy decisions?<sup>23</sup>

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<sup>23</sup>These perspectives were articulated by Eugene Skolnikoff of MIT in a letter to William Clark, dated September 22, 1988.

- What influences "the pace or response-time with which scientific information about threats of significant perturbations in the geosphere and biosphere is translated into government action" (Jacobson and Shanks, 1987:29)? More generally, which factors place environmental issues on national and international agendas? Which keep them there through time? Which institutional mechanisms might facilitate anticipatory as opposed to reactive agenda setting for issues of global change (Tang and Jacobson, 1988)?
- What strategies for environmental protection—what mix of education, markets, regulations, and laws—seem to work best for dealing with large-scale, long-term problems in specific cultural contexts (Tang and Jacobson, 1988)? What are the "attitudinal and political preconditions for effective regulation or resource management programs" (Jacobson and Shanks, 1987:29)?
- To what extent can methods of environmental protection be transferred from one country to another? What facilitates the transfer? What are the limits and barriers to one country's application of strategies successfully employed in another (Tang and Jacobson, 1988)?
- Despite the generally poor performance of both market and regulatory approaches to problems involving public goods and externalities, "some good solutions to borderline cases, such as research and development, are available through a third option, the 'not-for-profit' sector. This sector has played a very helpful role in such areas as public health and agricultural research associated with the 'Green revolution.'" What are the conditions under which it might play an equally important role in managing global change (McLaren and Skinner, 1987:544)?
- To what extent could trade and investment policies play a role in the management of global change? Do policies that encourage the spread of multinational business enterprises: (1) accelerate the diffusion of advanced pollution control and resource-management techniques; or (2) redistribute environmental degradation to less developed countries (Tang and Jacobson, 1988)?
- What are the "prospects for, and the strength of obstacles to, effective international coordinated regulation and resource management programs addressed to problems of international and global environmental degradation" (Jacobson and Shanks, 1987:29)?
- What new international frameworks, such as the concept of a "planetary trust" developed by Edith Brown-Weiss in the context of U.N. University studies on sustainable development, might provide

useful tools for the management of global change (Brown-Weiss, 1984)?

In addition to research on these questions, there is a need to provide fora in which such questions can be systematically pursued in close connection with research characterizing the likely nature, extent, and timing of global environmental change *per se*.

### Behavior and the Management of Global Change

Ultimately, it is certain patterns of human behavior that lead to environmental degradation, and other patterns that result in sustainable development. Research on global change needs to establish how relevant human behaviors are shaped, and how they can be altered as part of efforts to manage the long-term, large-scale interactions between people and their environments. A growing body of scholarship in economics, psychology, attitude change, communications networks, and social diffusion provides substantial foundations upon which the needed research can be built.<sup>24</sup> With some exceptions, however, this work has tended to focus on the determinants and control of individual behaviors. Global change problems, in contrast, highlight the importance of collective action and organizational behavior in shaping long-term, large-scale interactions between people and the environment.<sup>25</sup> A fundamental challenge in studies of the human dimensions of global change is to work toward a theory of human system behavior that encompasses all these relevant levels of social organization. On the way to such a comprehensive theory, several specific questions merit early attention in research on global change:

- Why do some individuals exhibit behaviors that contribute relatively much to the forcing global environmental change, while others choose to behave in ways that contribute relatively little?<sup>26</sup> To what extent do cultural factors, including income, social context,<sup>27</sup>

<sup>24</sup>See, for example, Bandura (1986), Lindzey and Aronson (1985), Rogers and Kincaid (1981), Schelling (1978), Winett (1986), and Stokols and Altman (1987).

<sup>25</sup>For a general review of the problems of collective action, see Olson (1971). For a recent anthropological perspective on organizations as the relevant units of behavior, see Douglas (1986).

<sup>26</sup>This question has been usefully addressed in the context of behaviors that concern energy use by Cook and Berrenberg (1981).

<sup>27</sup>The term "social context" is used here in the sense employed by Douglas and Wildavsky (1982).

access to relevant information, or immediate experience play a role in determining differences in relevant behaviors?

- Can some groups, organizations (e.g., corporations), or societies be identified as having exhibited behaviors consistent with environmentally sustainable development over extended periods? If so, what special characteristics set these groups apart? What, if any, is the distinctive role of "traditional" knowledge and practice in such cases?

- Given that most global environmental changes are both long delayed and common-property in nature, an individual has limited incentive to change his or her own immediate behavior in ways to reduce those changes. Neither markets nor state regulatory systems have proven particularly effective in dealing with the public good and externality dimensions of this situation (McLaren and Skinner, 1987:544). How can the needed collective behavior changes best be motivated and sustained in the context of global change problems? What can be learned from the recent rise of apparently powerful grass-roots environmental movements and other changes in the valuation of environmental concerns?

- What is the role of technical information and expert assessment in shaping behaviors relevant to global change? How can such knowledge be framed and communicated in ways that maximize its impact on the public and on support for social action?<sup>28</sup> In particular, experience in smaller scale environmental problems strongly suggests that technical information will be more effective in changing behaviors when it is conveyed along with assessments of alternative management actions, their likely consequences, and the prospects for fair distribution of costs and sacrifices (Brooks, 1986; White, 1988b). In what ways can such experience be used to improve the ability of technical information on global change to modify behaviors of individuals, organizations, and nations? What special challenges are posed by the international character of global change?

Finally, as in the case of research on institutional questions, there is a need to provide fora in which behavioral issues relevant to the management of global change can be systematically pursued in close

<sup>28</sup>The wording of this question is from Albert Bandura, in a comment on an earlier version of this report (letter to Dan Druckman of National Research Council staff, dated May 9, 1988). Bandura cites the work of attitude change theory (McGuire, 1969), decision theory in risk perception (Kahneman et al., 1982), and social cognitive theory (Bandura 1986) as providing relevant guidelines.

connection with research characterizing the likely nature, extent, and timing of global environmental change per se.

### SELECTED RESEARCH CHALLENGES

Previous sections of this paper have surveyed the principal elements involved in humans' interactions with the global environment and summarized the major unresolved questions regarding the character, causes, and consequences of those interactions. The objective of this section is to draw from those questions a small number of crosscutting research challenges that, due to their importance, complexity, and interdisciplinary character, might best be addressed as part of the formal U.S. contribution to the IGBP.

Selection of the "challenges" described here is based on the "external" criteria of importance described in the introduction of this paper, plus an assessment of the likelihood that results useful for the IGBP would emerge relatively promptly from a serious research effort. Priority is given to human dimensions of global change that achieve their importance through significant interactions with related climatic, biogeochemical, and biotic dimensions of change. Certain such interactions pose special challenges in that they can be addressed effectively only through substantial interdisciplinary research initiatives, which are unlikely to emerge from normal disciplinary priority setting and funding processes. These are highlighted here as topics that may benefit most from, and contribute most through, explicit integration within a focused research program constituting the U.S. contribution to the IGBP.

Five specific research challenges are outlined below as a stimulus to further and fuller discussion in the course of the IGBP planning process. It is recommended that study groups of leading scholars in the relevant fields be convened to develop more completely and critically the detailed research plans that will be required if these challenges are to be met.

#### Global Land Use Change

One major challenge for research on the human dimensions of global change is to build a better understanding of the processes underlying global land use change.

People's use of the earth's land surface is a key focus of the interactions between human and environmental systems involved in

global change. Human activities are transforming land surfaces in ways that have profound implications for ecosystems, biogeochemical fluxes, and at least regional climates (Bolin and Cook, 1983; Turner et al., in press). Conversely, changes in the global environments have major implications for human land use (Jaeger, 1988; Parry et al., 1988). Explaining the large-scale, long-term environmental changes of the last several centuries and predicting such changes for the future both require a deep understanding of the human processes underlying global land use change.

Four dimensions of a global land use study are envisioned. The first would be conceptual. It would entail the construction of a core conceptual model or theory of the causal relations that link underlying changes in culture (i.e., population, development, and values) on the one hand, and changes in environment on the other, to human choices that affect long-term, large-scale patterns in the use of the land. Among the key processes to be considered in the conceptual model would be those that determine the growth, character, and distribution of population (including rural-urban migration) and of agricultural development. Factors influencing relevant technology transfers and long-term changes in the trade linkages between places of production and places of consumption would also need to be included, as would the economic and institutional mechanisms involved in land use choice and regulation. Somewhat more elusive but almost certainly important would also be processes through which societies perceive the relation between their land use choices and the environment, and processes by which they attempt to intervene and make those relations more to their liking. Other factors and processes would be added to the conceptual model as the study matured.<sup>29</sup> Excellent foundations for a conceptual model of the human dimensions of global land use change are provided by the recent publications of the Dahlem Conference on resources and development and the SCOPE/ICSU land transformation project (McLaren and Skinner, 1987; Wolman and Fournier, 1987).

<sup>29</sup>For example, Pierre Crosson of Resources for the Future has outlined several key areas of basic research relevant to global land use change that need to be pursued over the long run. These include the regional impacts of climatic change, the socioeconomic preconditions for sustainable opening of the Latin American and African frontiers, the prospects for capitalizing on local knowledge in designing sustainable agriculture systems, the relation between land use and species diversity, the problem of yield variability and crop varieties, the effects of erosion on soil productivity, and the requirements for building the research capacity necessary for developing appropriate technologies for changing land use management. See Crosson (1986).

The second dimension of the study would be historical. It would document how the key variables of land use, population, agricultural prices, and so on, identified in the conceptual model have in fact changed throughout the world over last several hundred years. This work could build on the recent programs of environmental history brought together at the 1987 Clark University/IIASA/WRI project on "The Earth as Transformed by Human Action" (Turner et al., in press).

The third dimension of the study would involve in-depth regional case studies of the general relationships suggested in the conceptual and historical work. An explicitly comparative approach would be adopted. One possible framework, proposed by Pierre Crosson (1986) of Resources for the Future, would contrast regions occupying significantly different places in a two-dimensional field of density of population and density of economic or technological development (e.g., GDP/unit area). Priority regions might then include the tropical forests, semiarid but highly developed areas such as the American Great Plains, and the boreal forest. Other frameworks emphasizing other cultural and environmental differences could also be used. In any event, the choice of regions could usefully be made to complement areas selected for intensive study of natural processes through the "geosphere-biosphere training centers" proposed for the IGBP. The wealth of regional case studies prepared for the UNESCO Man and the Biosphere Program as well as the SCOPE and Clark University efforts noted above should also be considered. An obvious opportunity for bilateral and multilateral cooperation also exists here, as evident in proposals for land-use-related studies emerging from recent bilateral discussions between U.S. and Chinese (Tang and Jacobson, 1988) and U.S. and Soviet scholars (Kotlyakov et al., 1988).

Finally, the fourth dimension of the study would involve the construction of future scenarios of global land use change, and exploration of how alternative human choices regarding global change would alter those scenarios. Reference scenarios of the kinds of patterns of land use change that might be associated with major alternative paths of world economic development are essential to the planning of natural science research and monitoring in the global change program. A precedent exists in the useful (though inevitably imperfect) scenarios of future energy growth created by the economics community in support of studies on possible impacts of changing greenhouse gas concentrations in the atmosphere (e.g., Edmonds and Reilly, 1985; Nordhaus and Yohe, 1983). The key here is



to view the scenarios not as predictions, but as internally consistent reference cases that can be linked to readily understandable strategies of future development (Brewer, 1986; Chen and Parry, 1988; Lave and Epple, 1985). Some excellent Swedish work has recently been published on methods for assuring that such reference scenarios or "future histories" explore unlikely or surprising possibilities in the interactions between human and environmental systems, rather than simply summarizing conventional wisdom (Svedin and Aniansson, 1987).

A successful study of global land use change will require contributions from scholars expert in virtually all the elements of interaction between human and environmental systems that were described earlier in this paper. Due to the tight connections between agricultural development and land use, however, leadership in this venture might well be sought from the community of scholars interested in global, long-term patterns of agricultural development. Studies related to the global land use project proposed here have recently been recommended by a number of groups.<sup>30</sup>

### Industrial Metabolism

A second major challenge for research on the human dimensions of global change is a better understanding of the "metabolism" of productive and consumptive processes through which industrial societies force changes in the earth's environment.

As noted earlier, industrial civilization's transformations of material and energy resources constitute major sources of global change. Explaining the large-scale, long-term environmental changes of the last several centuries and predicting such changes in the future thus require a deep understanding of the changing "metabolism" of industrial society. Such understanding does not now exist, except for isolated technologies and waste products.<sup>31</sup> It needs to be created as

<sup>30</sup>For example, the SCOPE land use project (Wolman and Fournier, 1987), an ad hoc group on Social Science Contributions to the IGBP convened by the U.S. National Research Council's Commission on Behavioral and Social Sciences and Education (DeFries and Druckman, 1988), and the China-U.S. Workshop on Human Dimensions of Global Change (Tang and Jacobson, 1988). A thoughtful discussion of the possibilities for such a study appears in an unpublished note entitled "Some comments and suggestions on a social science component of the IGBP" prepared by William E. Riebsame of the University of Colorado in response to an earlier draft of this report (letter to William C. Clark, dated May 17, 1988).

<sup>31</sup>The case of chlorofluorocarbon emissions and stratospheric ozone depletion offers

part of a research program on global change. The central goal of an industrial metabolism study would be to understand and document how processes of industrial production transform resource inputs into outputs that must be absorbed and processed by the environment. A materials and energy balance approach would be central to the study, which would seek to develop a rigorous and quantitative understanding of the production and consumption processes involved in transforming basic material flows relevant to global change. The specific categories of industrial activity considered in the study would be selected to provide the most useful interaction with the natural science components of the global change program. The focus would likely include processes related to the flows of heavy metals, sulphur, and halocarbons.

Paralleling the land use study recommended above, four dimensions of an industrial metabolism study are envisioned. The first would be conceptual. It would entail the selection of materials, energy uses, and consumption processes of most relevance to global change, the construction of a materials and energy balance framework covering selected production and consumption activities, and specification of the causal factors determining the rates of transformation of those materials and energy flows. Considered would be the demographic, economic, and institutional factors underlying long-term trends in energy conservation and in the intensity of materials embodied in end-use functions (Goldemberg et al., 1987). Considerations of technology life-cycle (Ayres, 1987) and changing patterns in the places of materials production and consumption (Chisholm, in press) would also be included. Recent studies on materials cycling in global change led by Robert Ayres at IIASA and Carnegie Mellon University provide an example on which this work could usefully build (Ayres and Rod, 1986; Ayres and Tarr, in press).

The second dimension of the study would be historical. It would involve documentation of how particular material and energy resources have been metabolized through production and consumption processes over periods of decades to centuries. Where appropriate or

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a simple example of the need for some form of future scenarios as part of a global change research effort. Much attention has been devoted to the creation of such scenarios, and the most sophisticated recent probabilistic assessment (Hammitt et al., 1987) constitutes a significant improvement over early trend extrapolations. Nonetheless, it could do no better than assume that chlorofluorocarbon use in the long run would increase proportionally with global economic growth, and that economic growth would follow the trajectories assumed in the best models of energy use and carbon dioxide emissions noted earlier.

necessary from the perspective of the natural science investigations of global change, a world-scale perspective would be adopted. The spatial pattern of sources and sinks of industrial metabolites would merit special attention. The Clark University program on environmental history noted earlier will serve as a useful point of departure (Turner et al., in press).

The third dimension of the study would involve in-depth regional case studies of the general relationships explored in the conceptual and historical work. An explicitly comparative approach would be adopted, ideally along lines set to complement the regional studies of land use change described above. Again, the choice of regions would also endeavor to reflect the areas selected for intensive study of natural processes in the "geosphere-biosphere training centers" of the IGBP. Opportunities for multilateral cooperation in this work should prove to be especially strong.

Finally, the fourth dimension of the study would involve the construction of future scenarios of industrial metabolism and associated materials and energy exchanges with the environment. The objectives and approach outlined for the land use scenarios would apply here as well. The previously noted RFF study on atmospheric change and world development suggests the kinds of results that might be obtained (Darmstadter et al., 1987).

Again, the contributions of a wide range of scholars of the human system will be required if a major study of industrial metabolism in global change is to succeed. In this case, however, leadership might be sought from members of the engineering community and students of technological change. Studies related to that proposed here have also been recommended by a number of groups.<sup>32</sup>

### Usable Knowledge of Global Change

A third major challenge is to make knowledge about global change more useful as a guide to human action. As noted above, technical information, popular perceptions, and fundamental values interact closely in shaping human choices. Unfortunately, research

<sup>32</sup>These include the International Federation of Institutes for Advanced Study initiative on human responses to global change (IFIAS, 1987) and the Ann Arbor workshop reported in Jacobson and Shanks (1987). A new U.S. National Academy of Engineering program on technology and environmental change addressed this issue directly in an August 1988 workshop at Woods Hole, Massachusetts (White et al., 1988).

in understanding the components of choice has rarely been as integrated as the components themselves. The goal of this study would be to break new ground in developing an integrated understanding of how to improve the utilization of knowledge in human choices relating global change. Toward this end, the study would focus on determining how the interplay of assessment methods, perceptions, and values might be modified in ways that make possible more informed human choices on problems that arise through the long-term, large-scale interactions between peoples and their environments.

As argued earlier in this paper, some sort of regional focus would be required in order to address the great variety of environmental conditions, social structures, and human belief systems that shape the meaning of global change for people. One crucial aspect of providing more usable knowledge of global change would be to determine experimentally the most useful scale of "region" for use in assessments of global change. Another would be to develop ways of integrating individual, corporate, and state responses within this regional framework. However the regional issue is resolved, it would also be crucial to address explicitly the linkages among regions—how the human consequences of global change in one place affect assessments, perceptions, and consequences of global change in other places.

Four dimensions of a study on usable knowledge and global change are envisioned. The first would be conceptual. Following proposals set forth by the U.S.-China Workshop on Human Dimensions of Global Change (Tang and Jacobson, 1988), a framework would be developed for summarizing the major variables involved in human choices regarding global change. At a minimum, the framework would provide for examining the relation between basic cultural factors (e.g., relevant demographic, developmental, and institutional characteristics) and major components of choice (e.g., risk assessments, perceptions, values, and behavior per se). The purpose of the framework would be to provide a structure for the formulation of specific hypotheses, and for the construction and comparison of a variety of empirical case studies (see below).

A second dimension of the study would be methodological. One basic requirement is for better methods of monitoring changing patterns of peoples' perceptions and values regarding the long-term, large-scale interactions between human and environmental systems. As discussed below in the final section on selected research challenges,

there currently exists no capability for reliably monitoring these crucial determinants of the human dimensions of global change. At a minimum, an evaluation is needed of the relative feasibility and utility of global monitoring approaches relying on formal questionnaires as opposed to surveys of relevant material drawn from such sources as newspapers, literature, and art.

Another important methodological task would be the design and evaluation of approaches for resolving some of the major shortcomings of existing assessment methods that were identified in this chapter. Special attention would be given to methods for handling multidimensional syndromes of environmental change and for mapping assessments of such syndromes on a regional basis through the use of geographic information system technologies. Work would also be required on the technical difficulties of integrating values relating to the timing and uncertainty of consequences into the assessments. These methodological studies should be conducted experimentally. Each proposed improvement in assessment methodology should be evaluated in terms of its actual impact on the perceptions or values of potential assessment users.

The third dimension of this effort would consist of in-depth regional case studies. As suggested by the conceptual framework noted above, an effort would be made to compare the determinants of human choice on particular problems of large-scale, long-term environmental change across a wide range of cultural contexts. A strong historical orientation would almost certainly be useful here, leading to an understanding of how technical information, perceptions, and values have in fact interacted in shaping the evolution of various societies' responses to problems of global change.

Finally, the study would have a forward-looking dimension. This would seek to formulate recommendations regarding how the world's rapidly growing technical knowledge regarding global change could be better assessed, formulated, and communicated so as to make a more useful contribution to relevant human choices being made around the world. Once again, the hallmark of this work should be its experimental orientation. Alternative approaches to assessment and communication should be encouraged and then critically evaluated in terms of their actual impacts on perceptions, values, and behavior.

Leadership in the "usable knowledge" effort might be sought from scholars of human behavior, especially those who have been involved in studies of environmental hazards and risks. Experience

also suggests, however, that the organizations likely to be responsible for global change assessments—in the United States, notably the National Research Council, the Office of Technology Assessment, the appropriate executive agency groups, and the major nongovernmental organizations—should be intimately engaged in this effort if it is to have any chance of influencing their practices.<sup>33</sup> A number of other groups, including the World Commission and Environment and Development, have proposed studies related to that outlined here.<sup>34</sup>

### **Institutions for Management**

A fourth major challenge is to better understand the ways in which institutions at all scales interact in shaping the human system's capacity for coping with global change.

The institutional challenges posed by global change are substantial and varied. They range from providing for the basic research and monitoring that generate the technical knowledge base, through facilitating consensus building on required responses, to implementing coordinated actions in a great variety of local, regional, and national contexts. In a few cases, notably the recent protocol on protection of the ozone layer, interactions among institutions have evolved over a period of decades to the point that what began as the concern of a few scientists is beginning to translate into coordinated and effective

<sup>33</sup>The barriers faced in getting such institutions to adopt more self-conscious and experimental approaches to their work are profound. Several years ago, the U.S. National Research Council convened a special governing board committee on the assessment of risk in NRC reports with the explicit purpose of addressing many of the difficulties raised here (NRC, 1981). The report of the committee contained a number of excellent and feasible recommendations that have been virtually ignored by the NRC since their publication in 1981. In particular, subsequent NRC studies of the greenhouse effect and acid deposition suffer from shortcomings in the treatment of uncertainty that the NRC's own guidelines, if followed, would have substantially mitigated.

<sup>34</sup>The study proposed here might be one of the more productive ways to implement the WCED (1987) recommendation for a "global risk assessment." Related studies have been proposed by the International Federation of Institutes for Advanced Study workshop on Human Responses to Global Change (IFIAS, 1987), the U.S.-China Workshop on Human Dimensions of Global Environmental Change (Tang and Jacobson, 1988), and the new SSRC program on global change (Rockwell and Kasperson, 1988). Links between this effort and the planned International Decade for Natural Hazard Reduction would almost certainly be beneficial to both. The IDNHR is described in NRC (1987). In the form described by the NRC document, however, IDNHR would have serious shortcomings as a model for work on risk assessment and management for global change. In particular, the human dimensions of the proposed program strongly emphasize engineering over behavioral approaches to coping with hazards. Whether a more balanced treatment of human response can be evolved remains to be seen. For a critical review of IDNHR, see Mitchell (1988).

action at the international scale. In numerous other cases such as desertification, however, institutional mechanisms have been inadequate to translate concern into better management. Unfortunately, we have little understanding of why our institutions have coped better with some long-term, large-scale environmental problems than with others. We know even less about how present institutional structures might be redesigned better to cope with the increasing scale and urgency of global change.

Individual studies have, of course, illuminated important components of the overall environmental management picture. Thus we have treatments of the roles played by markets, international law and treaties, international organizations in the public and private sectors, international mechanisms for the exchange of scientific information, behavioral "regimes" based on informally shared norms, voluntary organizations, and so on (e.g., Caldwell, 1984; Carroll, 1983; Kay and Jacobson, 1983). There also exist a number of comparative studies examining different styles of environmental decision making at the national scale (e.g., Brickman et al., 1985; Enloe, 1975; Lundqvist, 1980; Vogel, 1986). Lacking, however, is a strategic or synoptic approach that puts these individual pieces into perspective, assesses their relevance and limitations with regard to the problem of managing sustainable development in the face of global change, and focuses attention on missing dimensions of present understanding.

The first phase of the study proposed here would be conceptual. On the cultural side, a framework would need to be developed for assessing how the capacity of human institutions to cope with global change is shaped by demographic, organizational, and developmental factors that vary tremendously from place to place around the world. On the environmental side, this effort would need to characterize how the environmental syndromes of global change are different, in a managerial sense, from the problems we have learned to deal with in the past. The rapidly changing spatial scale of human disruptions of the environment is clearly one important aspect, as is the increasing temporal scale (e.g., the long residence times of chlorofluorocarbons in the stratosphere). On the institutional side a framework would be needed for assessing how effectively different organizational approaches to research administration, regulation, and interjurisdictional coordination have dealt with the changing nature of environmental problems. The internal evolution of institutions would need to be considered here. It seems almost certain that the "maturing," on a time scale of decades, of structures as different as

the Sierra Club, the EPA, and United Nations Environment Program has profound—and not necessarily positive—implications for societies' capacities to manage global change. The present and potential role of the media in these processes would clearly merit special attention. The recent report of the U.S.-China Workshop on Human Dimensions of Global Change provides a detailed discussion of how this conceptual framework might evolve (Tang and Jacobson, 1988).

The second phase of the study would involve comparative historical case studies of how institutional structures, interrelations, and performance have co-evolved in the course of humanity's efforts to come to terms with specific problems of long-term, large-scale environmental change. Each study would adopt a global perspective from which to compare the performance of a number of local, national, and international entities. Special attention would be given to how institutions serving one functional or regional constituency interact with other institutions in attempting to come to terms with what global change means for their own action agendas.

The third phase of the proposed study would be synthetic. Its objective would be to draw from the theoretic and case study work specific recommendations for improving local, national, and international institutional structures for coping with global change.

The proposed study on institutions for the management of global change would require contributions from political scientists, legal scholars, students of international negotiations, and a variety of other social science disciplines. Close collaboration with the natural scientists engaged in research and assessment of global change would also be required. Leadership might be sought from scholars who have been active in comparative studies of institutional performance in environmental regulation. Studies related to that proposed here have recently been recommended by a number of groups.<sup>35</sup> An example of the way in which such a study might be structured is provided by the project on international institutions and the environment carried out several years ago by Kay and Jacobson (1983) under the auspices of the American Society of International Law.

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<sup>35</sup> Particularly strong cases are made in the reports of the Dahlem Conference on resources and development (McLaren and Skinner, 1987) and the Ann Arbor (Jacobson and Shanks, 1987) and U.S.-China (Tang and Jacobson, 1988) workshops on Human Dimensions of Global Change.



## Documentation

Each of the selected research challenges highlighted in this section, plus a number of the basic research questions raised above, has significant documentation aspects that are integral to its success. Two basic challenges concerning documentation of the human dimensions of global change should, however, be singled out for special consideration in the formal U.S. contribution to the IGBP.

### Environmental History

The first of these is an "electronic atlas" for unifying the documentation of environmental history research relevant to global change. As noted earlier in this paper, environmental history studies have advanced significantly over the past decade, and are now beginning to produce quantitative global data on century-scale interactions of human activities and the environment. More such data will emerge in the course of the global change program, particularly in the context of the land use and industrial metabolism studies suggested above. Now is the time to build a unified framework for organizing these historical data in a form that makes them readily accessible both to scholars of global change and to the regional and national planners who need to use that scholarship. The concept of an "electronic atlas" was raised by participants at the recent Clark University symposium on "The Earth as Transformed by Human Action" (Turner et al., in press). The intent was to create a spreadsheet and global mapping package designed for handling historical environmental data that could be run on desktop computers, but would be compatible with the more complex data bases being used for contemporary land use and remote sensing data. The software would be widely distributed for general use. The acceptance of new data sets into the official "atlas" would be determined by an editorial board of natural and social scientists, modeled on the boards that now govern the commissioning and acceptance of contributions to projects like the "world histories" of various academic presses. Disks containing parts or all of the current version of the atlas would be made widely available as a research and planning tool. Integration with the mapping functions of the "usable knowledge" effort outlined above might be contemplated.

### Perceptions and Values

A second proposed program of documentation concerns changing patterns of human perceptions of and attitudes toward global change. The Ann Arbor workshop developed a strong case that

because human beings and their institutions are ultimately responsible for actions that affect the Earth system, it will be important to monitor public attitudes and behavior. The sooner the international base-line surveys of attitudes and behavior concerning the ecosystem are conducted the better, for such base-line surveys will be an essential step in attempting to monitor and understand attitudinal change with respect to the issues that affect the Earth (Jacobson and Shanks, 1987:23).

We have passed through the time of people's first encounter with images of their planet viewed from space without any systematic survey knowledge of how that possibly revolutionary perspective may have changed our perceptions and values. If the next decade's research on global change is anywhere nearly as productive and surprising as its proponents hope, then the new knowledge it produces should affect us, the human component of global change, in ways we cannot now envision. It would be ironic indeed if we ended up knowing more about the changes in our planet than we know about the corresponding changes in ourselves. Some sort of periodic, global record of people's perceptions of, and values regarding, long-term, large-scale interactions between human and environmental systems should be an integral part of the documentation of global change.

Whether the "surveys" on which such documentation of global change is based should include a wide range of cultural products—e.g., newspapers, literature, art—as well as responses to specially prepared questions is an open methodological question addressed in the study of "usable knowledge" proposed above. In any case, however, the surveys will almost certainly be more illuminating if they are designed jointly by teams of scholars expert in both the environmental and the human dimensions of global change.

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**ANNEX A: PROGRAMS ON THE HUMAN DIMENSIONS  
OF GLOBAL ENVIRONMENTAL CHANGE:  
A PARTIAL LISTING**

[The purpose of this list is to encourage communication among the various institutional programs that are developing an explicit focus on the human dimensions of global environmental change. Many groups, of course, are pursuing studies related to this topic. Those listed here have undertaken efforts more or less directly related to the IGBP initiative. The named individuals should be able to provide further information. This listing is clearly incomplete.]

Center for Political Studies, University of Michigan [Harold Jacobson. Institute for Social Research. The Univ. of Michigan. Ann Arbor, MI 48106]

European Science Foundation, Standing Committee for the Social Sciences. [John H. Smith. ESF. 1 quai Lezay-Marnesia. F-67000 Strasbourg, France]

International Studies Association, Ad Hoc Committee on the International Geosphere-Biosphere Program. [Harold Guetzkow. Department of Political Science. Northwestern Univ. 601 Univ. Place. Evanston, IL 60208]

International Federation of Institutes for Advanced Study/ International Social Science Council/ United Nations University [Ian Burton. IFIAS. 39 Spadina Rd. Toronto, Ontario. Canada M5R 2S9]

International Union of Psychological Science, U.S. National Committee. [Mark Rosenzweig. Department of Psychology. Tolman Hall. Univ. of California, Berkeley, CA 94720]

Social Science Research Council. [Richard Rockwell. Social Science Research Council. 605 Third Ave. New York, NY 10158]

U.S. Department of State, Office of the Geographer. [George Demko. Office of the Geographer. Department of State. Washington, DC 20520]

U.S. National Academy of Engineering. [Jesse Ausubel. NAE Program Office, 2101 Constitution Ave., NW, Washington, DC 20418]

U.S. National Academy of Sciences, National Research Council.  
[Ruth DeFries, Committee on Global Change; Dan Druckman, Commission on Behavioral and Social Sciences and Education, 2101 Constitution Ave., NW, Washington, DC 20418]

U.S. National Science Foundation, Division of Social and Economic Sciences. [Roberta Balstad Miller. NSF. Washington, DC 20559]

### ANNEX B: THE PREPARATION OF THIS PAPER

The present composition of the Committee on Global Change reflects the early focus of the IGBP on the natural sciences. In order to pursue the committee's conviction that understanding of global change nonetheless must encompass human interactions with the natural system, it was therefore necessary to draw from a wide range of outside expertise in the social sciences and engineering. This task was facilitated by the many symposia, workshops, and studies on the human dimensions of global environmental change that the social science and engineering communities have recently conducted under impetus of the IGBP and its underlying themes. Instead of duplicating the work of these activities through committee-sponsored workshops, committee members or staff participated directly in the following efforts:

- the Ann Arbor workshop on an "International Social Science Research Program on Global Change" (Jacobson and Shanks, 1987);
- the Clark University environmental history symposium on "The Earth as Transformed by Human Action" (O'Riordan, 1988a; Turner et al., in press);
- the World Climate Impacts Program study on "Developing Policies for Responding to Climatic Change" (Jaeger, 1988);
- the ad hoc meeting of the National Research Council's Commission on Behavioral and Social Sciences and Education to review possible social science initiatives in support of a U.S. Global Change Program (DeFries and Druckman, 1988);
- the China-U.S. workshop on the "Human Dimensions of Global Environmental Change: Proposals for Research" (Tang and Jacobson, 1988);
- the Social Science Research Council project on "The Social Sciences and Global Environmental Change" (Rockwell, 1988; Rockwell and Kasperson, 1988);
- the National Academy of Engineering Woods Hole workshop on "Technology and Environment";

- the European Science Foundation workshop on "Environment and Development" (Hagerstrand, 1988; Nowotny, 1988; O'Riordan, 1988b); and
- the symposium organized by the International Federation of Institutes for Advanced Study (IFIAS), the International Social Science Council (ISSC), and the United Nations University (UNU) on "Human Response to Global Change" (IFIAS, 1987; IFIAS/ISSC/UNU, 1988).

In addition to this direct engagement, a number of recent reports prepared by other groups interested in the human dimensions of global change have been reviewed in preparing this paper. Among the most important to our conclusions are the following:

- the strategic review of future directions performed by the UNESCO Man and the Biosphere (MAB) Program's General Scientific Advisory Panel (UNESCO, 1986);
- the International Institute for Applied Systems Analysis program "Sustainable Development of the Biosphere" (Clark and Munn, 1986);
- the Social Science Research Council conference "Forecasting in the Natural and Social Sciences" (Land and Schneider, 1987);
- the Dahlem Conference "Resources and World Development" (McLaren and Skinner, 1987);
- the report of the World Commission on Environment and Development (the Brundtland Commission) on "Our Common Future" (WCED, 1987);
- the report of a Royal Society of Canada meeting entitled "Human Dimensions of Global Change: the Challenge to the Humanities and Social Sciences" (Braybrooke and Paquet, 1987); and
- the report of a joint U.S.S.R.-U.S.A. study on "Global Change: Geographical Approaches" (Kotlyakov et al., 1988).

This paper was prepared by committee member William Clark with the objective of synthesizing the substantive findings and recommendations of the work cited above, and of assessing the relevance of those findings to initial plans for U.S. participation in the IGBP. Earlier drafts of the chapter were extensively reviewed by members of the social science and engineering communities, whose assistance is gratefully acknowledged in Annex C.

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### ANNEX C: ACKNOWLEDGMENTS

Comments on earlier drafts of this essay from the following people have contributed significantly to its content and style: Jesse Ausubel, Richard Bishop, Harvey Brooks, Robert Chen, Jerome Clubb, Philip Converse, Chester Cooper, Joel Darmstadter, George Demko, John Firor, Roland Fuchs, Robin Gregory, Harold Guetzkow, Wayne Holtzman, Harold Jacobson, Robert Kagan, Roger Kasperson, Robert Kates, Roberta Miller, James Mitchell, Sherry Oaks, Ted Parson, Steve Rayner, John Richards, William Riebsame, E. Fred Roots, Norman Rosenberg, Mark Rosenzweig, Thomas Schelling, Stephen Schneider, T. Paul Schultz, Eugene Skolnikoff, Peter Timmerman, Barbara Torrey, Amos Tversky, Edith Brown-Weiss, and Dorothy Zinberg. A special debt is owed to Gilbert White, who, in addition to constructive criticism, provided unpublished manuscripts from which this paper draws heavily.

# Earth System History and Modeling

COORDINATOR: BERRIEN MOORE III

Because of the immense complexity of the earth system, we must employ models—reduced description of reality—to describe the system or its components. Modeling is, in a sense, simply the formulation of working hypotheses of how the system is structured. In the context of understanding and predicting global change the continued development of a variety of earth system and subsystem models is clearly needed in light of the underlying complexity. Model development generally places great demands on available contemporary data, and unfortunately, little independent information about the present is available for model testing. In addition, the ultimate objective of the IGBP to predict changes in the global environment places added burdens on model validation. As models of the earth system and its components emerge, they will generally be based upon the current state of the system and reflect processes and rates associated with the present environment. Thus reproduction of current dynamics is a basic but sometimes limited test of the models. To test them over a wide range of conditions, models must be exercised against the record of past environments.

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This paper has been compiled from discussions on earth system history at the workshops on ecological systems and dynamics and biogeochemical cycling, and further discussions within the committee.



The geologic record contains information about the earth's environment extending back as far as 3.8 billion years. Although incomplete and hard to interpret, this record becomes progressively more complete toward the present and is most complete in the Quaternary (<2 million years), the later Pleistocene ( $\leq 400,000$  yr), and especially in the Holocene (<10,000 yr).

The geologic record is particularly useful as it shows the range and direction of excursions in the terrestrial environment, for example, major glaciations between 450 and 250 million years and since 40 million years and global warming between 140 and 65 million years. An important aspect of this record is the evidence of rapid change from one mode of global environment to another. In some cases there is evidence that the rapid change may have been related to specific identifiable triggering events. For example, a change to what is basically the present pattern of oceanic circulation originated about 15 million years ago and appears to have been related to the closing of part of the Tethys Ocean in Iran (Woodruff and Savin, in press), which stopped a southward flow of hot saline waters into the Indian Ocean.

Paleoclimatic and paleohydrological research reveals numerous climatic events and trends that characterize the past few million years. These include histories of glacier extent, global ice volume, surface ocean temperature, abundances of  $\text{CO}_2$ ,  $\text{CH}_4$ , and other trace gases in the atmosphere, extent of forests and arid zones, and sea and lake levels. This information is provided by a global network of fairly continuous records that contain quantifiable environmental and proxy-climate indicators such as pollen, ratios of stable isotopes, and chemical and particulate concentrations. These natural "diaries" provide different sets of insights into the history of the earth, covering a variety of characteristic spans of time and space. The detailed records of the past 25,000 years, with a focus upon the past 1,000, should be particularly useful in providing specific tests for models of global change on time scales of decades to centuries.

### **RECONSTRUCTION OF THE ENVIRONMENTAL HISTORY OF THE EARTH**

The reconstruction of the earth's paleoenvironmental history began in earnest with the development of new geochemical tools developed in the middle of the twentieth century. The essential characteristics of environments over the last million years emerged from the

sedimentary records preserved within the ocean floors. Long-term ice core records bridge the gap between the longer records available from ocean sediment cores and the shorter, high temporally resolved histories available from pollen sequences in lake sediments, tree rings, corals, insect remains, and speleothems. Additionally, higher temporal resolution ice core records from high latitudes and carefully selected high elevation ice caps in both middle and low latitudes offer critically important shorter records with fine temporal detail.

The marine sediment record reveals that the warm global climates that characterized the past 10,000 years are but the interglacial phase of an ongoing glacial-interglacial cycle. Only 18,000 years ago, ice sheets covered most of Canada, part of the United States, and much of Northern Europe, with sea level some 60 to as much as 140 m lower, and with a climate much cooler and (on a global basis) drier than today. Analysis of various marine sediment properties (such as cadmium,  $^{13}\text{C}$  and  $^{14}\text{C}$  to  $^{12}\text{C}$  ratios, and species variability) provides evidence of circulation patterns, temperature, salinity, biological processes, and distribution of nutrients, carbon, and oxygen. Sediment records on land provide evidence that the pattern of ice-age vegetation in temperate North America was very different from that of today, and a clear picture of how the vegetation responded during the past 18,000 years to a continually changing climate is emerging.

Insights into climates of the past few tens of thousands of years have been derived from cores drilled in the Greenland and the antarctic ice caps (Dansgaard et al., 1984). The oxygen-isotope and deuterium ratios of the ice reveal the temperature at which the water in the snow evaporated from the surface of the ocean, modified to some extent by the condensation temperature and by global ice volume. Therefore, changes in these ratios with depth provide a record highly correlated with changes in polar temperature between glacial and interglacial epochs. The record suggests that very rapid changes in climate may have occurred during glacial times, and that the glacial to interglacial transition may be relatively rapid (Berger and Labeyrie, 1987). Records of dust in ice and oceanic sediment suggest altered patterns of arid zones and atmospheric circulation.

As discussed in the background paper on biogeochemical dynamics concentrations of atmospheric trace gases have been measured in the entrapped air within ice cores. From such studies, we know that  $\text{CH}_4$  concentrations have doubled in the air since A.D. 1600 and were much lower during the last ice age, and that the  $\text{CO}_2$  content of the

air was 30 percent lower during the time of glacial maximum than over the last 10,000 years.

The acidity of ice cores reflects the temporal history of the atmospheric concentration of acid aerosols at high latitudes and hence the volcanic flux of sulfate particles, which interact with solar radiation. This quantitative record of explosive vulcanism can be compared with other geologic records of climate in order to assess the role of such events in the alteration of climate. Further, the record of anthropogenic alteration of the sulfur and nitrogen burden of the atmosphere is most clearly captured within the ice core records.

Pollen and other microfossils—e.g., diatoms, and insect remains trapped in lake and bog sediments—reveal past patterns of biota in the surrounding region and physical properties of the lake. These proxy indicators, through the use of transfer functions calibrated to modern species distributions, can be used to infer changes of seasonal temperature or precipitation. Although time lags may be introduced in lateral migration by the slow dispersal of seeds of certain species, lake and bog cores do allow inference of both spatial and temporal changes of climate over much of the earth's land area. This field is relatively undeveloped considering its potential.

The thickness of wood in an annual tree ring where growth is limited by climate provides a direct measure of growth in that year, and hence of local climate. For some applications, seasonal resolution can be obtained by analysis of early and late wood in a single ring. In many areas of the world, such records can be extended back several hundreds of years, and in some cases several thousand years, providing unique insights into the history of our environment. Furthermore, the tree ring records contain important information about the isotopic character of the past atmosphere and hence about valuable biogeochemical histories.

Finally, past glacier fluctuations can be inferred from moraine limits, stream terraces, and other geomorphic indicators. Lake level data can be obtained directly by age-dating materials (gastropods, tufa) that grew in shallow water or may be obtained indirectly by examination of the organic or inorganic content of age-dated cores taken from lake basins. Groundwater recharge events can also be age-dated and the carbon and oxygen stable isotope ratios used to infer change in temperature or moisture source region.

## MODELS

Models are needed to synthesize our understanding of the interactions of the various components of the biogeochemical, hydrological, and physical-climate systems, including the coupling with vegetation systems. Models provide a framework for analyzing the impacts of human activities on the earth system. Another related synthetic role of models is to optimally assimilate observations of complex fields of related variables, as is now done in global weather prediction systems. Such assimilation constrains the observations through known physical laws and uses these physical laws to extrapolate and interpolate from the observations to data-poor locations. For example, important land properties such as soil moisture cannot be measured directly on the regional scale, but can be tightly constrained from estimates of rainfall patterns and evapotranspiration, which would result from assimilation of observations into a four-dimensional model of the system.

Models of the physical-climate system are ideal tools for synthesis of paleoclimate and hydrological data and, conversely, are dependent on such data for validation of their capabilities to predict future global change. However, it is necessary to improve the coordination of paleo-observations and their synthesis by climate modeling studies, on both global and regional scales. Emphasis must be placed on the verification of model sensitivity to various climate forcings, including the present seasonal cycle, volcanic dust veils, and factors driving paleoclimatic episodes. These are all potential "natural experiments" that provide tests of model performance. In addition, the behavior of the interacting climatic subsystems must be understood, and the data must be synthesized and enhanced.

Global climate models are in part an outgrowth of weather forecasting activities. More emphasis is needed on the linkages to other parts of the climate/hydrological systems and on the wide range of temporal and spatial scales over which these occur. The scientific community at large needs to understand the underlined physical relationships of the parameterizations and, the limitations of the models in order to use them appropriately and more effectively in the development on the models. Tools and concepts that have been developed by other communities, such as geographical information systems and hierarchy theory, may prove to be valuable for the study of climate problems.

In addition to global approaches, a focus on regional climate change processes will be especially valuable. Global simulations can

be extended through the use of mesoscale models embedded in the global model to provide required detail. Only with such an approach can topographically complex regions such as the western United States and western China be adequately treated.

Models of the earth's biogeochemical system are, in comparison with climate models, less advanced. In part, this is due perhaps to a greater level of complexity. There has been progress, particularly in the area of the global carbon cycle. From the simplest perspective, one can consider the earth biogeochemical system as a three-box model: an atmosphere, a terrestrial biosphere, and an ocean including the marine biosphere. In this context, the questions are as follows: what is the flux of various biogeochemical compounds ( $\text{CH}_4$ ,  $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{N}_2\text{O}$ ,  $\text{NO}_x$ ,  $\text{NH}_3$ ,  $\text{COS}$ ,  $\text{DMS}$ , and so on) between the boxes, what controls these fluxes, and how are they affected by anthropogenic activity? Obviously, in order to give even first-order consideration to these questions, the heterogeneity of the "boxes," (the atmosphere, the terrestrial biosphere, and the ocean) must be considered explicitly.

Models of the chemistry of the atmosphere that reflect a range of spatial and chemical complexity are under development. In terrestrial systems, serious methodological questions regarding scale partly reflect past traditions of ecosystem modeling at a relatively small scale (hectares to square kilometers) as well as the difficulties inherent in the system. New work, however, is emerging at the regional to global scale that has been encouraged by advances in the integration of models with geographical information systems and remote sensing. Major physical oceanographic programs such as The World Ocean Circulation Experiment and complementary biogeochemical programs such as Joint Global Ocean Flux Study set the stage for rapid advances in ocean biogeochemical modeling. But in all of these areas, we are faced with extremely difficult problems of methodology and data availability, as well as a multiplicity of feedbacks at varying spatial and temporal scales that connect the physical-climate system to the biogeochemical system.

### **DECODING THE PAST: CHALLENGING GLOBAL MODELS**

Tests of models of global change will come from data from the past, as will insights into fundamental processes that operate on time scales of many decades to centuries. We are a long way from a

fully satisfactory model of the causes of past major global changes. The recent records of  $\text{CO}_2$  and  $^{18}\text{O}$  in the Vostok, Antarctica, ice core (Barnola et al., 1987; Lorius et al., 1985) reveal a close linear relationship between temperature and  $\text{CO}_2$  abundance, as previously reported in the Dye 3, Greenland, core (Stauffer et al., 1985). However, the Vostok core provides the first detailed look at an interglacial/glacial transition about 120,000 years ago. The  $\text{CO}_2$  concentration remains high for nearly 10,000 years as the  $\delta^{18}\text{O}$  proxy for temperature exhibits a rapid decline into full glacial conditions. Either we understand very little about the physical and chemical relationships between climate (temperature) and the biogenic and oceanic cycling of  $\text{CO}_2$  and/or there are problems in the  $\delta^{18}\text{O}$  temperature interpretations. The  $\text{CH}_4$  record poses similar problems. On shorter temporal scales problems also arise. What is the cause of the linear rise in  $\text{CO}_2$  from the middle of the eighteenth century to the middle of the nineteenth century? Is it anthropogenic forcing, or is it related to the end of the Little Ice Age? The accurate reconstruction of these histories requires improving and synthesizing our understanding of the physical, chemical, and biological processes.

The modeling and data analysis efforts could be usefully focused on two key temporal periods: the past 25,000 years and the most recent 1,000 years. In both cases, special consideration could be given to periods of rapid change since large abrupt changes in the global system (Younger Dryas, Little Ice Age, major episodes of volcanic activity, and El Niño events) offer special challenges and tests of both model capabilities and our understanding of the causes of climate change.

### The Past 25,000 Years

Emphasis should be placed upon the reconstruction of the earth's environmental history over the past 25,000 years. This period encompasses the range of conditions from full glacial stage to full interglacial. It is easily dated and is well preserved; numerous deep ocean cores have been retrieved, and there are extensive ice core and pollen records. Over this period, the global climate system went from the coldest extremes of the last ice age to the present interglacial with accompanying large changes in patterns of temperature, precipitation, ice cover, and distributions of ecosystems.

Over the past 25,000 years, there were also large changes in

biogeochemical cycles reflected in large changes in global concentrations of  $\text{CH}_4$  and  $\text{CO}_2$ . Isotopic tracers such as  $^{18}\text{O}$  and deuterium can be used to track the global climate and geochemical changes that occurred over this period. The first extensive look at a global reconstruction of full glacial conditions resulted from the Climap (Climate Long Range Investigation and Mapping) Program (Climap Project Members, 1981). Land records directly describe variations in vegetation cover and lake levels. For instance, global vegetation maps are emerging from regional compilations of pollen data. As the geographical coverage increases, these maps will provide reconstructions of increasing global biomass as  $\text{CO}_2$  concentrations increased at the glacial-interglacial transition. Measurements of the  $^{13}\text{C}$  content of  $\text{CO}_2$  and  $\text{CH}_4$  can provide important clues to the processes responsible for the changing concentrations of these gases in the atmosphere. Postglacial conditions have been mapped by the Cooperative Holocene Mapping Project (COHMAP Members, 1988).

One suggested modeling thrust toward interpreting the paleorecord over the past 25,000 years is the application of mesoscale models coupled to global models. Such mesoscale models can provide simulated weather data as input to runoff-infiltration models, and can couple to lake thermal-evaporation models as well. Thus simulations of lake-level variation could be compared to the actual record. On the biological side, the model climate can be used via response-surface transform techniques to recreate aspects of the vegetation history of a region. The simulated pattern of vegetation in space and time might then be compared to a proxy-data network, e.g., pollen and microfossil and macrofossil records. Such a mesoscale model would need accurate representations of surface physics, and a grid fine enough to resolve important variations in topography and surface characteristics over large watersheds. Its hydrologic components would require careful development and validation. Lake modifications of regional climate may have a significant impact on the growth of large lakes. Proxy data sets on several time scales are needed over the region of interest including that provided by a coring program both onshore and offshore in multiple lake basins. If methods to adjust apparent groundwater ages are perfected, the timing of lake-level rise in one area could be compared to the timing of groundwater recharge in the same or other areas.

### The Past 1000 Years

Special emphasis should be placed in global change research on the past 1000 years, which incorporates the Little Ice Age and the entire industrial period. Within this time frame, numerous proxy records can be incorporated with archeological, historical, and instrumental records. The records for the past 1000 years are often annually, and in some instances seasonally, resolvable. The research focus should be the history of the climate (particularly temperature), atmospheric chemistry, terrestrial vegetation, and patterns of oceanic circulation and production. This focus offers an excellent opportunity to exercise models of the planet's biogeochemical system as it interacts with the physical-climate system on time scales of decades to centuries, which are particularly relevant to global change.

This intensive study of the naturally archived records of the past 1000 years should include comparisons with available "ground truth" data contained in direct historical accounts such as weather and sea records. While this sort of comparison is routinely done in the course of sharply focused studies of specific environmental parameters—as in calibrating tree ring widths in a given location in terms of soil moisture or other meteorological parameters—such a study has never been organized for multiple parameters focused on an extended test period. A more organized study of this type would serve several purposes that would benefit the IGBP. Specifically, it would

- illuminate more fully the transfer functions needed to interpret natural archives by this use of direct, historical data as "ground truth";
- establish the potential and limits of reliability of an organized, multiparameter study in which naturally archived data from different sources are combined to gain a deeper knowledge of a specific period or of specific events such as volcanic eruptions; and
- maximize what is known of global change in the past 1000 years—a period that includes an increase of a factor of 30 in world population (with accompanying changes in land use), the industrialization of much of the world (with accompanying changes in atmospheric chemistry), the onset of modern worldwide intensive agriculture, and the full span of the most recent distinguishable feature of global climate change (the Little Ice Age, ca. 1450 to 1850 A.D.).

The naturally archived data that should be employed include



ice cores from Greenland and the Antarctic (hydrogen and oxygen isotope ratios; trace gases, including  $\text{CO}_2$  and  $\text{CH}_4$  and their isotopic compositions; sulfate and nitrate concentrations; and pollen, atmospheric aerosols, and volcanic dust at seasonal resolution within distinct annual layers); ice cores from carefully selected temporal latitude glaciers (hydrogen, oxygen, and carbon isotope ratios, other chemical species, aerosols and pollen, and volcanic dust at seasonal resolution in easily distinguished annual layers); tree ring data, including ring width and hydrogen, oxygen, and carbon isotope ratios (annual resolution with the potential of discriminating spring/summer seasons in early and late wood); high-resolution terrestrial sediment sequences (pollen, runoff at decadal resolution); lacustrine sediments (pollen, lake level at annual resolution); and cores from coral reefs (hydrogen, oxygen, cadmium, and carbon isotope ratios with annual resolution of evidence of humic acid).

The period of truly extensive "ground truth" data will be limited to at most the last 100 years of this 1000-year period, and for most parameters of interest, to an even shorter, more recent period. It is the most recent epoch—say the past 50 years—that will provide the most meaningful tests and illuminate most usefully the transfer functions and their limits. Less extensive and far more regional historical data are nevertheless available and should be gathered together for a systematic study of the longer 1000-year span. Real-time studies would provide a strong focal point for better understanding the relationship between processes and the resulting record. In this study the more extensive suite of meteorological and environmental parameters taken during the IGBP would be compared, for example, with real-time samples of precipitation in the glaciated areas where ice cores are drawn. This step would make a substantial contribution to the establishment of the real significance of measured parameters such as  $^{18}\text{O}:^{16}\text{O}$  and  $\text{H}:\text{D}$  ratios that are routinely measured in ice, sediment, and coral cores.

Thus these relatively detailed data from ice, ocean, and terrestrial cores reflecting the changes occurring during this period will provide a rigorous test of earth system models and thus will be a step toward validating these models for use in projecting future change. An obvious difficulty, however, remains—the anticipated future rates of change will likely be far greater, and the forcing functions will be different.

The challenge to the modeling community is to construct models of the biogeochemical and physical-climate systems (or components

thereof) that are consistent with the multiparameter observation sets in the historic record and that are also consistent with the very recently observed transients in the system such as bomb  $^{14}\text{C}$  or fossil fuel  $\text{CO}_2$ . This is a major challenge; in seeking to meet it, it may be particularly useful to focus specifically upon periods of rapid change within either the 1,000-year record or the 25,000-year period.

### Abrupt Change

Ice core results from both the polar regions and the high-altitude tropics contain evidence of rapid transitions from one mode of climate to another. The dust, sulfate, oxygen isotope, and  $\text{CO}_2$  records change from full glacial to interglacial conditions in less than one century in the Dye 3 core (Hammer et al., 1985; Herron et al., 1985). The dust concentrations in the Camp Century, Greenland, core show an equally abrupt transition (Thompson, 1975). The transition from Neoglacial Little Ice Age to current conditions in the Peruvian Andes occurred in 3 years as reflected in the particulate (soluble and insoluble) and oxygen isotopic records (Thompson et al., 1986; Thompson and Mosley-Thompson, 1987). The Younger Dryas, a brief cool period interrupting the Wisconsin (Wurm)/Holocene transition, is another example of an abrupt transition from one set of conditions to another.

Fine-scale sampling of peats and laminated lake sediments provides detailed studies of vegetation change. High priority should be given to studies of vegetation dynamics during periods when independent data from ice cores record rapid changes in the environment. In this way lags in vegetation or ecosystem response can be measured, and the extent to which response lags blur the record in proxy records of rapid environmental change can be better understood.

### RESEARCH CHALLENGES

As discussed above, *research efforts should focus on reconstruction of earth system history over the past 25,000 years to encompass the range of conditions from full glacial to full interglacial stages, with special emphasis on the past 1,000 years to cover the period of intensive human interactions with the system.* Provisions for selecting specific events or eras within these time frames need to be established. In particular, high-resolution studies are important for documenting the rate of change of the earth system in the past. For

example, the resolution of marine cores at present is too coarse to distinguish between instantaneous changes caused by threshold effects from a nonlinear response to steady changes, such as a switch from one mode of ocean circulation to another. New studies must be initiated to focus on periods of rapid change to document the time scale of change, as well as to determine rates of changes of different responding variables in the system. It will be important to compare marine and terrestrial sites to identify differences in temporal responses in different parts of the earth system.

*Models need to be developed to interpret the response of the earth system to past changes.* Specifically, models of global biogeochemical cycling that consider nutrient interactions and of the hydrologic cycle in specific geographic regions need to be developed. Moreover, efforts need to focus on linking global models of the biogeochemical system to global climate models. Physical and geological models are required to develop and test hypotheses about causes for changes in biological systems observed in the paleorecord, such as Cretaceous-Tertiary and late Pleistocene extinctions. Combining paleoecological records with geomorphic evidence and ice core records is necessary for determining cause-effect relationships. In particular, investigations of the causes of transitions from one ecosystem type to another are essential for predicting future changes.

*Finally, an accessible data and information system, with the aim of assembling various proxy historical and instrumental data into a coordinated and validated archive, is an essential component of a research effort on earth system history.*

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